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R. A. Fisher

Fig. 1—Stripping the heads from grain, leaving the straw for braid or for fuel. Japan.

Soil Management

By the Late

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Author of "The Soil," "Irrigation and Drainage," "Physics of Agriculture," "Ventilation for Dwellings, Rural Schools and Stables" and "Farmers of Forty Centuries." Professor of Agricultural Physics in the University of Wisconsin, 1888-1901; Chief of Division of Soil Management, U. S. Department of Agriculture, 1901-1904.

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PREFACE

This volume is the outgrowth of the remarkable soil investigations of the late F. H. King of the University of Wisconsin. Professor King had projected a book on Soil Management many years ago. For the past ten years he had been assembling material with this idea in mind. His untimely death prevented the fulfillment of this purpose, but fortunately for the agricultural and scientific world his widow, Mrs. C. B. King, has brought together such of his papers and lectures as contain materials that he would have worked into an organized form. His study of Chinese, Korean and Japanese agriculture was part of his plan for the work on Soil Management, which he was unwilling to put forth until he knew something of this oldest management with its present marvelous results.

The chapter on the study of Far Eastern agriculture has been collected by Mrs. King

from ten different lectures and papers which he had already prepared. While this volume is not as complete as it would have been had Professor King lived, the investigations are of such world-wide importance and of such rich practical value, that the material has been assembled in order that many of the conclusions from the work of a lifetime of one of the world's greatest soil investigators might be available in the easiest accessible form.

C. W. BURKETT.

New York, March 25, 1914.

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CHAPTER I

PRODUCTIVE CAPACITY OF FIELDS AS INFLUENCED BY SOIL MANAGEMENT

THE management of soils to establish, to increase and to maintain a high productive capacity of fields is one of the oldest and most extensively practiced arts of industrial life. Most barbaric and all civilized peoples have fostered it. No other art or trade engages the attention and absorbs the energies of so many families.

With the vast and ever-increasing demands made upon the materials for food, for apparel, for furnishings and for cordage, which are the products of cultivated fields, better soil management must grow more and more important as populations multiply. With the increasing cost and ultimate exhaustion of mineral fuels; with our timber vanishing rapidly before the ever-growing demands for lumber and paper;

with the inevitably slow growth of trees and the very limited areas which the world can ever afford to devote to forestry, the time must surely come when, in short-period rotations, there will be grown upon the farm the materials from which to manufacture, not only paper and substitutes for lumber, but fuels as well. Not the complete utilization of the power of every stream which reaches the sea, reinforced by the force of the winds and the energy of the waves which may be transformed along coast lines, can meet the demands of the future for power and heat; and hence only in the event of science and engineering skill becoming able to devise means for transforming the unlimited energy of space through which we are ever whirled, with an economy approximating that which farm crops now exhibit, can good soil management be relieved of the task of meeting a portion of the world's demand for power and heat.

While the lands which may be laid under tribute by good soil management, to augment future supplies, extend from the shore lines

of the sea to the snow lines of the mountains and of the polar zones, each year they are becoming unavailable by hundreds of square miles through the expansion of cities and the multiplication of homes and summer cottages; through the extension of railways, trolley lines, canals and highways, and through their appropriation for military uses and park reserves. To meet the rapidly increasing demands upon these inevitably decreasing areas, the methods of soil management must be improved; the underlying sciences, in their relation to it, must be developed and the practices squared to their laws and teachings, just as in great commercial, mining and manufacturing industries these have been and are being squared to theirs. This can only be effectively done through organized effort directed by that training and experience which the complex and difficult nature of the problems demand, but which no body of farmers has ever been or can be expected to become able to command. Those industries which, from their nature, can syndicate large amounts of cap-

ital in their interest may and do, economically and effectively, command scientific methods and skill for the express purpose of developing those underlying principles which good business men are quick to recognize as indispensable to commercial success. But in agriculture, in only a few of its commercial and manufacturing phases are any of these means of improvement available, and hence the extreme necessity for, and the appropriateness of, government aid in bringing to a working basis the knowledge of the underlying principles of soil management and of leading phases of other agricultural practices.

Up to the present time the burden of effort has been expended in developing the commercial and manufacturing phases of agriculture, rather than upon those conditions which determine and maintain a high productive capacity of the soil. Such an evolution has been natural, rational and, up to the present time, perhaps, most advantageous; but we are fast approaching that stage when it will become of the greatest importance—

not that less attention shall be given to advancing the manufacturing and commercial phases of agriculture, but when much more and effective effort must be given to those conditions which tend to increase the yield per unit area on all types of soil.

Universally, the world over, under all climatic conditions and for all types, the bad management of soils has been found to greatly reduce their productive capacity, the fall often being, for some crops, to as low as one-fifth of the virgin productive power. Such great reductions, too, have generally been effected in comparatively brief periods, often during the life and management of a single man. Within my own personal experience, and doubtless within that of many of you, inherently rich soils whose normal productive capacities ranged from 30 to 45 bushels of wheat have been reduced, by faulty management, to 15 and even as low as eight bushels per acre, and this during a period of cropping covering much less than 50 years. Reductions in productive capacity like these are not due to changes in climate,

in cultural methods, in potency of seed, in varieties of wheat, nor to changes in any other outside conditions; they have resulted from profound, but as yet not well understood alterations within the soil itself; from changes which a sufficiently early knowledge and care in its application undoubtedly could have averted.

The mean yield of wheat in the United States during the last ten years of the century just closed was only 13.2 bushels per acre,* scarcely one-third, certainly not one-half, what the normal virgin capacity of the soil once was. From nearly 40 millions of acres in wheat, which should have yielded between 1,000 and 1,500 million bushels per annum, we have realized but little over 500 million bushels. Instead of gross earnings which should have amounted to from 650 to over 900 million dollars annually, there has been realized only 330 million dollars, an annual shortage of the wheat crop alone large enough, could it have been averted, to give to each of the 48 states and territories

*Hunt, "The Cereals in America," p. 122.

between seven and 14 million dollars each year of that decade.

To put greater emphasis upon this enormous shrinkage in productive power, let me say that during the period under consideration the mean yield per acre of wheat in Germany, where more attention has been devoted to the maintenance of soil fertility, was 26 bushels per acre, and in the United Kingdom it exceeded 31 bushels. Notwithstanding the fact that in European Russia the mean yield of wheat has fallen as low as nine bushels per acre, yet the aggregate wheat product of Europe, according to statistics, exceeded that of the five other continents by as many as 292 millions of bushels, and this, too, notwithstanding the long time those fields have been under cultivation and notwithstanding the fact that the United States had ten acres in wheat for every square mile of surface in all Europe. Moreover, with Europe's large output of wheat she produces at the same time, of oats, of barley and of rye nearly fourfold the crop grown in North America; the figures stand-

ing 4,362 million bushels for Europe against 1,099 millions for North America. Even when we combine the yields of wheat, oats, barley and rye grown in North America with our great staple, maize, the total output aggregates but 3,965 millions of bushels, as compared with 6,413 millions harvested each year in Europe.

And when we recall that the producing power of the same lands for other crops has also much depreciated, it is easy to realize that we are here confronted with a problem of public policy, directly affecting material prosperity, scarcely exceeded by any other now engaging the attention of statesmen and of philanthropic effort. To double the productive capacity of the wheat lands of the world without materially increasing the cost of production per acre means to reduce the price of bread one-fourth, but what this would mean in added comfort and freedom, and in physical, intellectual and spiritual uplifting for the millions who are carrying the manual burdens of the world, and for the young men and women of these classes,

impelled by their inherent aptitude for more intellectual labors, who are striving to secure for themselves the general and technical training necessary for assuming those labors, is beyond the power of monetary standards to express.

To maintain a high productive capacity in soils which are normally rich, to restore this capacity again to those in which it has been reduced, and to materially increase the yield in soils which are naturally poor, is clearly a matter of the highest order of national concern. Only when this has been done does it become possible to secure the largest returns from the best cultural methods, from the most improved breeds and strains of either plants or animals, or from a full extension of commercial and manufacturing methods for the disposal of agricultural products. The selection of crops with special reference to their adaptation to certain types of soil, to climatological and to market conditions, to the development of drought, disease and insect-resisting strains, and the selection and care of seed

are all important lines of procedure tending to increase yield; but back of and before these and all else is the soil itself, which must be carried to and maintained at the highest productive capacity before, either singly or in combination, the other lines of effort can yield their highest returns. If a hardy strain of wheat, for example, will increase the yield on a 13-bushel soil to 16 bushels per acre, on the same soil brought into a 26-bushel condition, the hardy strain ought here to increase the yield beyond three bushels per acre, making it 32 or more, instead of 29 bushels. Where the yield of wheat on a given field has shrunk from 40 to 15 bushels per acre; where that of oats has shrunk from 70 to 20 bushels and that of corn from 80 to 25 bushels per acre, there is no reason to hope that the introduction of new varieties or the use of more vigorous seed will force the yield up to the old standards. The main help must be sought through the restoration of the old physical, chemical and biological conditions of the soil itself, which will put the productive

capacity inherent in the soil back where it was when the yields were high.

Having said this much, in a general way, regarding the great importance of more attention being given to the soil itself, I desire to bring to your consideration, as briefly but forcibly as I may, a few fundamental facts and principles which lie at the foundation and must direct all lines of effort aiming to secure higher yields from our fields through a better, more economical and more rational management of the soil.

There is nothing which can do so much, in a business way, for any line of industry as a clear, full understanding of the great facts and principles which, if intelligently adhered to and applied, lead with certainty to the desired results. In illustration of what is here referred to let me call your attention for a moment to the manner in which the world's supply of nitrogen is maintained in the soil today and has been through unnumbered ages. For many years it has been known that green plants draw their main supply of carbon directly from the air in the

form of carbon dioxide or carbonic acid gas. But it is only within the memory of the youngest in this audience that the real source of that very important element, nitrogen, has been made known to the agricultural world. The most careful observers and the most thoughtful practical men among farmers of all countries and throughout all history had associated an observed increase of crop following the growing of different members of the clover family upon more or less exhausted fields. But they could see no necessary reason why the growing of clover on a field and the removal of the crop from the ground should give to it a higher productive power; and so, except where there was some other reason than that of improving the productive power of the field, there was no incentive to grow regularly in the system of rotation some one or another of the leguminous crops, like the clovers, alfalfa, lupine, cowpeas, soy beans or sainfoin. For a long time it was held that the exclusive source of nitrogen for the higher plants was the organic mat-

ter of the soil, and this, too, notwithstanding the fact that it was continually being washed from the soil in the form of very soluble nitrates and being carried to the sea and even escaping in large quantities into the atmosphere in the form of free nitrogen. When, finally, the matter came under rigid investigation by men of science, there followed a battle extending over years, during which the opponents in the fray hurled against one another all the weight of experimental evidence, cogency of logic and massiveness of personal authority which they could command, and there was a stage in the combat when it looked as though error would be securely seated on the throne of truth, when this conviction of many practical men would be relegated to the category of planting and butchering in the right phase of the moon.

Indeed, it was true that the highest authorities of the time and the most careful and rigid experimenters, thinking and planning from a mistaken point of view, the more cautiously they moved and the more

thoroughly they safeguarded their lines of attack to avoid the introduction of sources of error, the more unquestionably did their results appear to bear out the conviction, at that time thoroughly rooted, that none of the ordinary higher plants are able to add to their nitrogen supply from the air itself. But in the many repetitions of experiments which were conducted, particularly among those which, it was held by opponents, did not sufficiently guard against sources of error, there were found gains of nitrogen, and these led to looking at the problem from different points of view; and, while the conflict with its story was long, the real truth was finally brought into the light, and we now know with the definiteness that twice two make four that when a vigorous leguminous crop is matured upon the ground the soil is made absolutely richer by the addition of very considerable amounts of nitrogen extracted from the soil air by the microscopic organisms dwelling and feeding in the tubercles or nodules found on the roots of the vigorous plants of most, if not all, of the

large clover-pea-vetch-bean family. And now that this great principle or method of adding the indispensable nitrogen to the soil has been demonstrated with absoluteness, farmers are able to proceed with the assurance of certainty rather than that of faith. The result is that a thousand apply the truth where one did before, and there is perhaps no discovery in all the wide realm of agriculture which will be able to do so much in the permanent winning of bread as this.

I wish now to emphasize for your stronger conviction three other very fundamental truths upon which enduring economic methods of soil management must forever rest. These are:

1. The necessity for a sufficient amount of room in the soil, not only in the portion turned with the plow, but throughout the effective root zone.

2. The existence in the soil of large amounts of plant food materials, but not in available forms, and which it must become the business of soil management to transform into available condition with sufficient

rapidity to meet the need of heavy yields.

3. The necessity for an ample crumb-structure of the soil throughout the effective root zone, which bad management breaks down and which good management builds up and renders more stable.

The urgency of an abundance of room deep in the soil is very great. In the first place, we do not sufficiently appreciate that the soil of a field is in reality a pasture upon the internal surface of which available plant food materials grow, through the mutual interaction of a multitude of soil organisms, organic matter, moisture, air and the roots of crops, living and decaying, all of them operating together to bring into solution the more insoluble forms of potash, lime, magnesia and phosphoric acid, so that when the roots of crops spread themselves out over the extensive internal surface, carrying a rich growth of soluble plant food materials, they find themselves in an ample pasture of nutritious feed, and growth is rapid. But the first great requisite of this pasture is room—broad surfaces upon which large amounts of

water may be stored to become charged with dissolved plant food materials, over which organic matter may widely spread to constitute the feeding ground of those microscopic forms of life which turn its nitrogen and other plant food elements into forms available to crops, and these internal surfaces far enough apart to give strong and deep ventilation and ample space into which the roots may spread and find abundant opportunity to set the soil grains aside to make room for due enlargement.

Upon the accompanying chart there has been represented, by drawing to proper scale, the volume of the component portions of the surface foot of a soil possessing about the medium amount of room which is found in a soil of average productive capacity. The bottom cube in the diagram stands for a cubic foot of undisturbed surface soil, in its normal field condition when well settled toward the end of the growing season after having been plowed 6 to 7 inches deep in the spring of the same season. The second cube represents the volume the dry soil would

PER. CENT	LBS.	CU. IN.
.115	.084	.878
2.680	1.961	2.680
22.13	13.81	382.5
33.63		581.1
44.24	73.18	764.1
6.75		
100.0	86.99	1728

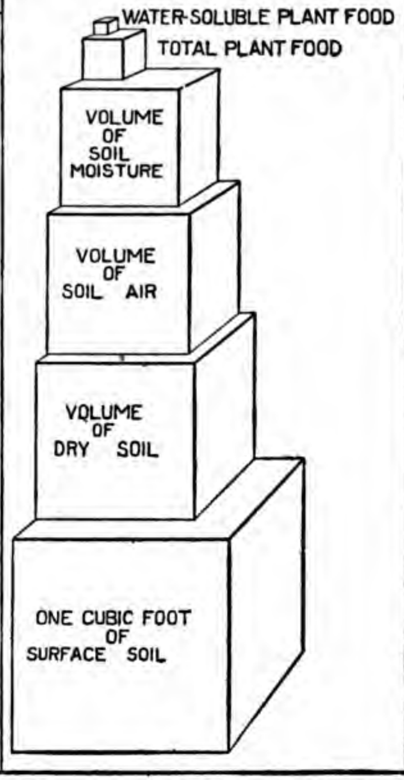


Fig. 2—Showing the relative amounts of dry soil, soil air, total plant food and plant food materials soluble in water, contained in one cubic foot of average surface soil in the United States.

occupy with the moisture and the air removed and with the soil so consolidated that all open spaces are obliterated. In this condition its volume would be 764.5 cubic inches, or 44.24 per cent of the whole cubic foot. The dry weight of this soil is 73.176 pounds, while the dimension gives a cube a little more than 9 inches on each edge. The third cube on the chart represents the volume of the space in the foot of surface soil which is occupied by air when the amount of moisture present is very near the best amount for good crop conditions. In it there are 581.1 cubic inches of space occupied by air, comprising 33.63 per cent. That is, the surface foot of soil in good moisture condition possesses an amount of room through which air may circulate and in which the roots of crops may develop, which is rather more than one-third of the entire volume, expressed by a cube 8.3 inches on each edge. The volume of water carried in a cubic foot of surface soil is represented relatively by the fourth cube on the chart, which contains 382.5 cubic inches, or 22.13

per cent of the whole volume, and contained by a cube a little less than 7.3 inches on each edge. This amount of water represents nearly 2.66 inches in depth on the level over the surface, and if the space occupied by air were also filled with water the combined amount would overspread the surface to a depth of 6.69 inches.

There are few places in the United States where the amount, character and distribution of rain are such as to make maximum yields possible, and hence it is a matter of great importance that the roominess of the soil be maintained of such an amount and of such a character that whatever rain falls during the growing season may be quickly taken in without puddling the surface and without so completely filling the soil as to seriously check soil ventilation during any long interval of time.

Thorough underdrainage is the first requisite for developing and maintaining roominess and openness deep in the soil. Next comes a deep incorporation of organic matter through a rotation which includes

clovers and grasses. The roots themselves open the soil and, carrying the organic matter into the subsoil, induce a deeper penetration of earthworms, ants and other burrowing animals. Moreover, the deep incorporation of organic matter assists the action of frost and of shrinkage, due to drying, in developing the crumb structure which renders the openness more efficient. The occasional deep turning under of stable and green manures and of roughage of all kinds is extremely helpful; and it is not sufficiently appreciated that most organic matter is more efficient turned under than when left to decay at the surface.

AMOUNT OF PLANT FOOD CARRIED BY SOILS

It is very important to understand that there is present in the soil a very large amount of the different plant food elements; that only a small portion relatively of that present exists in immediately available form; but that good and bad methods of soil management exert a very marked influence

upon the rate at which the plant food elements present in the soil are transformed into the condition available to crops.

Taking Maxwell's complete analysis of a composite sample made up of soils from the grounds of many of the experiment stations in the United States, and 73.176 pounds as the mean weight of a surface foot of soil, the following table gives the amount of the different essential plant food elements per acre, expressed in tons:

TONS PER ACRE OF ESSENTIAL PLANT FOOD ELEMENTS IN THE SURFACE FOOT OF SOIL.

K Potash	Ca Lime	Mg Magnesia	N Nitrogen	P Phosphoric acid	S Sulphuric acid
tons	tons	tons	tons	tons	tons
20	8.9	7.0	4.0	2.4	.6

These amounts constitute 2.68 per cent of the dry weight of the soil, and their aggregate volume is represented relatively by the fifth cube on the chart, 2.73 inches on an edge and weighing nearly an even two pounds for each cubic foot of surface soil. Thus it is seen that of the nearly 43 tons of essential plant food elements carried, about

one-half is potash (K), one-fifth is lime (Ca), one-sixth is magnesia (Mg), one-twelfth is nitrogen (N), one eighteenth is phosphoric acid (P) and one-eightieth is sulphuric acid (S).

But the effective root zone in any soil adequately underdrained and of the proper degree of openness is fully three to four feet in depth, and hence the roots of a crop may be spread out through a soil mass carrying three or four times the amounts of all of the plant food elements designated in the table above, excepting only nitrogen, and in this case Warington found the surface four feet at Rothamsted to carry 5.2 tons per acre. Four thousand crops of wheat yielding 40 bushels of grain and 3,600 pounds of straw per acre will not gather from the soil as much potash, lime or magnesia as are carried in the surface four feet of soil. There is phosphoric acid enough for 1,100 such crops, sulphuric acid enough for 700, but nitrogen enough for only 155 such crops of wheat. Nevertheless it must be remembered that with more plant food, even of

nitrogen, than will suffice for one hundred such crops of wheat within the reach of roots beneath the surface of every field; with the rainfall, with the sunshine and with the temperature to a measurable extent unchanged; with better seed, better varieties, fuller knowledge, more efficient tools and higher skill in management, the richest of our virgin soils have fallen from a productive capacity of 40 bushels of wheat per acre to one as low as 20 and even much less during periods so short as 25 years. What has been the cause of these shrinkages? Can the virgin productive capacity of such soils be restored? Can it be economically maintained, if restored? If it can be economically restored and afterward maintained, then by what means and by what methods? These are the vital and fundamental problems of soil management.

AMOUNT OF WATER-SOLUBLE PLANT FOOD ELEMENTS IN SOIL

We have tried to fix in our minds the very important fact that within the surface four

feet of every well-managed field there are carried, in the aggregate and on the average, something more than 120 to 160 tons of the essential plant food elements. We desire now to emphasize another even more important fact, namely, that the great bulk of these large amounts of plant food elements is locked up in the form of substances which dissolve with extreme difficulty in water, and, while it is true that none of the plant food materials become available to crops until they are dissolved in the soil moisture, it is nevertheless fortunate that the great reservoir of plant food materials is filled with forms so difficultly soluble. Were this not so, the percolation of rain through the soil would carry away so completely the plant food materials that even in regions of abundant rainfall the land would be a desert, and only in the arid regions, where leaching cannot occur and where irrigation must be resorted to, could crops be grown without the heaviest and ever-repeated applications of fertilizers.

The smallest cube represented on the

chart shows, relatively, the aggregate volume of the essential plant food elements which were recovered from eight soil types, four of which were good and four poor, by leaching quickly through thin layers of them 55 times their dry weight of pure water, a layer of water which would cover the surface to a depth of some 16 to 18 inches. This cube of plant food soluble in water, derived from one cubic foot of surface soil, a little less than 0.1 of an inch on an edge, constitutes .1148 per cent of the dry soil, thus making a weight of a little more than an ounce per foot of surface soil, and 3,660 pounds, or 1.83 tons, per acre. The amounts of the respective plant food elements so recovered are given in the next table.

PLANT FOOD ELEMENTS REMOVED FROM THE SURFACE FOOT OF EIGHT SOILS, WITH PURE WATER.

Amounts in pounds per acre of surface foot.

	Potash K	Lime Ca	Magnesia Mg	Nitrogen N	Phosphoric acid, P.	Sulphuric acid, S
Good soil,	663.5	2,292.0	766.6	71.61	202.6	1,116.0
Poor soil,	586.9	626.8	293.4	35.70	84.83	548.1

Number of crops of wheat required to remove the above amounts.

	Potash K	Lime Ca	Magnesia Mg	Nitrogen N	Phosphoric acid, P.	Sulphuric acid, S
Good soil,	22.7	293.8	286.3	1.1	17.3	241.6
Poor soil,	20.1	80.4	101.0	.5	7.2	118.6

From this table it will be observed that there existed in the four good soils very much more of all the essential plant food elements in a form which could be recovered with pure water than were carried in the poor soils. In the aggregate the water-soluble plant food elements from the good soils exceeded those recovered from the poor soils more than 2.8 times, while the yield of corn and potatoes was nearly 2.5 times greater.

The figures given above refer to the surface foot only, but it must be remembered that the roots of crops penetrate the soil to a depth even greater than four feet; and further than this, through capillary movement of the soil moisture, the dissolved plant food materials are carried from the fourth, third and second feet upward into the surface foot. Because of these relations the surface four feet of these eight soil types were examined to determine the amount of the different plant food elements which could be recovered from them by treating them only three minutes in five times their weight of water.

The total amounts so recovered are given in the next table.

PLANT FOOD ELEMENTS RECOVERED FROM THE SURFACE FOUR FEET OF EIGHT SOIL TYPES BY WASHING BUT THREE MINUTES IN FIVE TIMES THEIR WEIGHT OF PURE WATER.

Amounts in pounds per acre of surface 4 feet.

	Potash K	Lime Ca	Magnesia Mg.	Nitrogen N	Phosphoric acid, P	Sulphuric acid, S
Good soils,	264.8	1,016.4	348.3	82.0	113.6	1,379.0
Poor soils,	182.4	395.4	177.4	30.2	64.3	388.6

Number of crops of wheat required to remove the above amounts.

Good soils,	9.1	130.3	130.0	1.2	9.7	298.5
Poor soils,	6.2	50.7	66.2	.45	5.5	84.1

Here, again, it is seen that the good soils have yielded to the three-minute washing in pure water more of the essential plant food elements than the poor soils did, and also more than enough from the surface four feet of soil of each and every element for a crop of 40 bushels of wheat and 3,660 pounds of straw per acre. Indeed, there was recovered of both potash and phosphoric acid enough for nine such crops; and there is little doubt that if the washing of the same samples had been repeated 11 times in corre-

sponding amounts of water, as was done in the first series cited, nearly 11 times as much of these two elements would have been recovered; and we see that while the plant food elements carried in soluble form in soil are small in comparison with the amounts present which are not readily soluble in water, these forms are nevertheless large in the good soils, and in the surface four feet enough of all except nitrogen for many large crops, could it all be used.

It is not sufficiently appreciated, although it should go without saying, that a strong soil moisture solution, well charged with all the essential plant food elements, making it a thoroughly balanced ration for the crop growing upon the field, is indispensable to large yields. Indeed, just as in the case of growing and producing animals, the body must be kept charged with blood rich in all that is essential to increase, so it must be with crops; their sap must be loaded and to spare with everything that makes for growth; and just as a rich blood can only be maintained out of a rich solution in the alimentary

canal, ever reinforced by good air, so a strong plant sap can only be continuously supplied to the crop when the roots are ever immersed in a soil solution rich in all that is needed, and well aerated. The next table shows how different was the plant sap in the crops growing on the good and on the poor soils.

AMOUNT OF PLANT FOOD ELEMENTS IN THE SAP OF PLANTS, PER EQUAL AREAS, GROWING ON GOOD AND ON POOR SOIL.

	Potash K	Lime Ca	Magnesia Mg.	Nitrogen N	Phosphoric acid, P	Sulphuric acid, S	Total
	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.
Good soil,	126.3	19.0	21.0	21.5	11.8	5.5	205.1
Poor soil,	47.9	3.7	3.5	3.1	4.6	1.3	64.1

From this table it is seen that the same number of plants, growing upon an equal area of good soil, were able to take up from the soil through the soil moisture in the same time nearly three times as much potash, as measured by the amount contained in the plant sap, over five times as much lime, six times as much magnesia, seven times as much nitrogen, more than double the amount of phosphoric acid, and four times

the amount of sulphuric acid. Associated with this stronger nutritive solution in the soil, and with the sap of the plants richer in the elements which contribute to growth, there was a yield on the stronger soil nearly 2.5 times that which developed on the poorer soil.

We have reason to think that, in the ultimate analysis, an exhausted soil is one in which it has become impossible for natural processes to maintain a sufficiently strong nutritive solution to meet the needs of rapid growth. But with such large amounts of the essential plant food elements present in the root zone of most agricultural soils, and with so much as we have shown to be present, even in the poorer soils, which may be readily removed by water, it may appear strange, at first thought, that reduced yields can result from a deficiency of plant food materials. Observations, however, have shown that the plant sap during vigorous growth is, and apparently must of necessity be, strong in all of the plant food elements. But in order that this may be so maintained,

we have reason to think that the soil solution outside of and in contact with the absorbing roots must be maintained correspondingly strong. Certain it is that if we place salt meat in pure water, it becomes less salt; and if we wish to render it more salt, we must place it in a brine more concentrated than that present in the meat; and we believe that the same relations hold for plants, although sufficient proof is not at hand, and a different view is held by many. If the view here expressed is correct, any highly productive soil must be rich in the readily water-soluble plant food elements, and it must carry through the growing season much more of these than will be required to produce the crop on the ground, or else it must possess the conditions which permit the soluble food materials to develop faster than they are needed. It need not seem strange, therefore, that soils increase in productive power with the addition of manures and fertilizers, even where it may be shown that there is present in the soil at the time, and in readily soluble form, more

than the crop can remove. If the physical condition of a given soil—its openness, its extent of internal surface and its crumb-structure—is such that it must carry in soluble form more than can be removed by a dozen crops in order to be able to supply the plant food elements as rapidly as the one crop can use them, then such a soil must decrease in productive power whenever any one of the essential food elements cannot be delivered to the crop as rapidly as needed, even though there be present in the soil enough for a thousand crops.

SOURCE OF THE SOLUBLE PLANT FOOD ELEMENTS

The water-dissolved plant food elements, which are the direct source of the plant food derived from the soil, come from two ultimate sources, (1) the mineral portion of the dry soil itself, and (2) nitrogen from the soil-air fixed by micro-organisms. But, indirectly, the immediate sources of the plant food elements carried in the soil moisture

are the slow solution of the soil grains themselves and the decay of organic matter which overspreads and comes in contact with their more or less extended surface. The amount of internal superficial area given to the root zone of a field by the aggregate surfaces of the soil grains is a very important factor of productive capacity. This is so because it is over this surface that the soil moisture is spread to become charged with the essential plant food elements derived from the soil grains themselves and from the decay of organic matter disseminated among them. It is upon this surface that the soil organisms live which hasten the decay of the organic matter and so charge the soil moisture with plant food materials; and it is against the same surface that the root hairs of crops place themselves to appropriate both the moisture and what it has dissolved. The internal soil surface of every field is, therefore, a pasture where plant food grows and upon which crops, through their roots, feed.

The extent of this internal surface is very

great and very different in the different soil types. Let me try to help you to better realize this very fundamental and important truth. Imagine a cube of granite one square foot on each face. If this cube were lowered into water and raised from it again, it would come out overspread with a sheet of water measuring 6 square feet in area, for the cube has six faces. Let this surface be dusted over with finely ground stable manure, well charged with the soil organisms which bring about its decay. A spear of corn planted at the center of the top face of this cube would find itself in possession of a pasture area measuring 6 square feet, over which its roots could place themselves to imbibe moisture and the food materials with which it becomes charged as solution of rock and decay of organic matter takes place.

Now imagine the cube quartered. The area of the surface of granite, of the sheet of water, of the pasture, is doubled for there are now four cubes each with an area of 3 square feet and, with no more soil, the corn roots have a pasture of 12 square feet. There

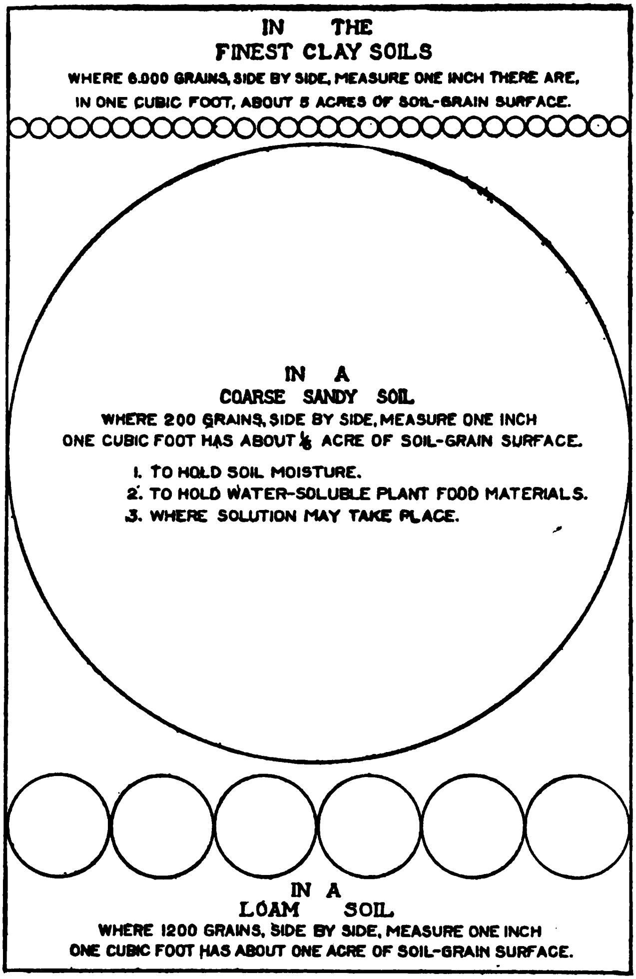


Fig. 4—Showing by circles the relative diameters of grains of coarse sandy soil, finest clay soil and loam soil; 636 times average diameter.

are 12 square feet upon which solution may take place, to which water may adhere, where organic matter may decay, where the roots may feed. If now each of these cubes is quartered, their surfaces will again be doubled, and we shall have a cubic foot of soil whose aggregate surface measures 24 square feet. Make the cubes one-hundredth of a foot on an edge, and the total surface becomes 600 square feet. If, again, the cubic foot of granite is divided into cubes one thousand of which together measure a foot, the separate pieces may be readily seen singly with the unaided eye, and it would be so coarse that we would call it a fine sand, and yet the total surface to which water could adhere, upon which chemical action and solution could take place, and against which the root hairs could place themselves to feed, would be 6,000 square feet, or one-seventh of an acre per cubic foot.

On the chart herewith there have been represented, all on the same scale, circles having the effective diameters of three soils, the finest clay, the average loam and the

coarse sandy type. In the finest clay type it requires 6,000 of the soil grains, set in line and in contact, to measure an inch; in the loam type, 1,200; and in the coarse sandy soil, 200. Of the particles of the finest clay soil 30 are required to span the diameter of a single grain of the coarse sandy type, and five of them are needed to measure one of the mellow loamy soils. From our illustration of the cube of granite you will readily see that of internal surface to which water may adhere, upon which soluble and dissolved plant food materials may be formed and stored, and where soil organisms and the roots of plants may feed, the finest clay soils possess thirty times that which is possessed by soils of the coarse sandy types, and five times that possessed by the loams.

So great is the internal surface of soils that its extent must be expressed in acres per cubic foot, and in the three cases chosen for illustration the coarse sandy soil possesses no less than one-sixth, the loam, one, and the finest clay soil more than five acres of soil-grain surface for each and every

cubic foot of such soil in the field. These areas aggregate, for the surface foot and per acre of field, more than 10, 60, and 300 square miles, respectively, for the coarse sandy soil, the loam and the finest clay type. Thirteen hundred, 270, and 45 square miles of pasturage in the four feet in depth of the root zone surface, per acre of crop, seem like an enormously extravagant allowance upon which to grow grass and grain and vegetables and fruit, and yet it is what Nature has provided. Verily, every farmer is a multimillionaire in the acres of internal soil surface from which he wins his harvest! And now I must repeat once again that it is over such vast areas as these that the soil moisture of the effective root zone is spread, from which it dissolves the mineral ingredients it carries and against which both these and that which comes from the decay of organic matter is stored for the use of crops.

With these conceptions of the differences between soils of different types and of the manner in which the soluble conditions of the plant food elements accumulate so as to

be appropriated by crops, the great importance of a deep and abundant incorporation of the organic matter in the soil can be appreciated, because through it decay takes place in contact with a much larger soil surface, more room is given for the soil organisms to work, the plant food materials produced may be concentrated upon and retained by a much larger surface, and there is greater opportunity for the roots to come in contact with the plant food developed and stored.

Deep incorporation of organic matter is accomplished by a thorough turning under of the roughage of the fields, using the jointer and chain where necessary; through frequent moderate and occasional deep turning down of both stable and green manures; by growing in rotation the deep-rooted leguminous species, together with the densely and deep-rooted grasses. No form of organic matter for incorporation in the soil is so valuable as stable manure. It is so because it has been placed in superlative physical condition by being finely ground,

Fig. 3—Showing relative size of cotton plants where stable manure was used and where it was not, on soil of sandhill type. Water-soluble salts washed from surface 4 feet under large plants, 953 pounds per acre. Water-soluble salts washed from surface 4 feet under small plants, 822 pounds per acre. Mean yield of lint, large plants, 522 pounds per acre. Mean yield of lint, small plants, 450 pounds per acre. Middle plant, from compact sandy loam where roots did not develop so deep.

Fig. 6—Korean rice paddies in a valley rising rapidly into the hills.

Fig. 7—Garden areas near Tsinan, Shantung Province, China.

and because it is doubly charged with the most available of plant food materials. The great problem is to get it incorporated with the soil deeply and thoroughly while it is yet at its full strength. To throw it about to weather in the rains and the sun is no less irrational and but little less wasteful than would be a similar practice with the hay and the grain from which it was produced. Excessive applications to the soil, too, like the over-feeding of live stock, is literally throwing money away, besides making some effort to do so. Next to the waste of fertility which occurs before getting the manure to the field, is that of applying it unevenly and over too small an area. Moderate applications, well spread and well incorporated with the soil, are far better than heavy dressings applied at long intervals. The danger is, where heavy dressings are applied, that the fermentation will be carried too far and a very large part of the nitrogen be lost in the form of the free gas. Maximum amounts of stable manure are seldom made on any farm. All the roughage

and waste of the fields would be much more efficient as a fertilizer if it could be first used as an absorbent, and to be most efficient when used in this way it should be cut fine. Stable manure is but finely ground roughage, saturated with the best kinds of plant food materials, but stock may be made to sufficiently saturate two or three times the amount they will eat, and thus increase the fertilizer product of the farm at least twofold. Nothing can increase the yield of the corn belt so much as to shred or cut finely the stover, now wasted on so many fields, and make it into manure by using it as feed or as an absorbent and then effectively apply it to the fields.

GOOD TILTH

Good tilth, or a thorough, deep and strong granulation, giving a well-marked crumb-structure, is the most important physical condition of any soil. The great urgency of the crumb-structure in soil grows out of the fact that in all but the coarsest

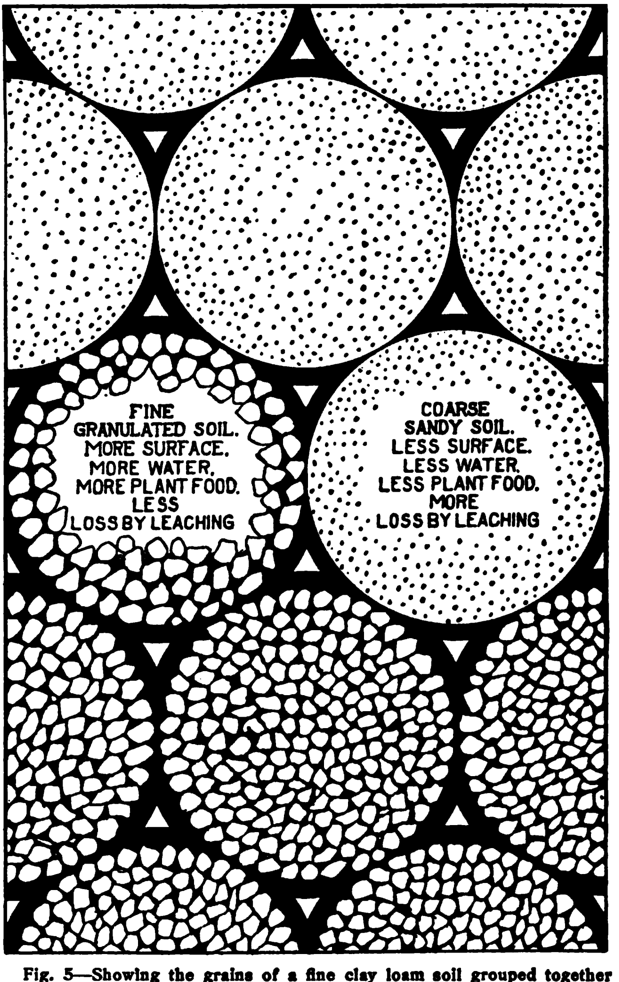


Fig. 5—Showing the grains of a fine clay loam soil grouped together in the form of granules equal in size to the average grain in a coarse sandy soil. The dotted circles represent single solid sandy soil grains, the solid black represents the films of water surrounding the soil grains and soil granules and filling the spaces between the grains making up the granules of the clay loam soil.

sandy soils the individual grains are so small that when they are not bunched together the capillary pores are so minute as to make them like the potter's puddled clay, nearly impervious to both air and water. But when the fine soil particles are collected and more or less cemented into larger compound grains, much as popcorn is made into balls, then there is opportunity for the roots and the root hairs to advance between them, placing themselves so as to absorb the moisture and plant food materials which surround and are contained within them. Upon the surfaces of these compound grains the microscopic soil organisms place themselves where their products of decomposition have the best opportunity to act as a solvent upon the soil and also where the products may easily diffuse into and be retained by the granules against loss by leaching.

When a soil is well and strongly granulated each compound grain becomes like a tiny sponge, which may maintain itself full of water highly charged with plant food materials, to be sucked out by the root hairs

when they develop alongside of them; and hence a strongly granulated soil has a greater capacity for both available soil moisture and for plant food. It will be clear that where the soil is strongly granulated, so that the larger particles have a spongelike openness, these will hold within themselves and away from their immediate surfaces large amounts of plant food which cannot be so readily leached out, for then the rains drop down rapidly through the larger passageways without strongly affecting the solution that is within the compound grains themselves. Besides, where this structure exists and the action of the roots has partly dried the granules out and at the same time removed a portion of the plant food which they had stored, then when a rain does come which causes the water to move downward, whether by capillarity or by percolation, these partly emptied granules will draw the water with the plant food which it may carry back into themselves and thus hold both the moisture and the other nourishing elements up nearer to the surface where they

will be more efficient. And so it is that a strongly granulated soil may profitably be more highly fertilized than one which is not, and so maintained at a higher stage of productive power. To illustrate, when a solution carrying potash was allowed to percolate very rapidly through the four poor and the four good soils, to which reference has already been made, the soils which were most highly granulated and which possessed the highest productive capacity were able to absorb from the solution and retain within their granules at the rate of 1,736 pounds of potash per acre of the surface foot, while the four poor soils, less strongly granulated and possessing less internal surface, were able to take from the solution at the rate of only 893 pounds per acre.

In proof of the greater power of highly granulated soils to hold the plant food elements back against leaching, the same eight soils were treated with the same amounts of the same kinds of stable manure, and then, after an interval of six months, they were all leached in the same manner and with the

same amounts of pure water, to see how much of the plant food elements would be retained. The results obtained are given in the next table.

	Tons per acre.			
Amounts of manure applied	25	50	100	200
	Pounds per acre.			
Potash in manure	109	218	436	870
Potash retained:	Pounds per acre.			
Four good soils	91	182	384	663
Four poor soils	77	160	276	448

The table shows how different was the power of the two groups of soil to hold back, against leaching, the potash which had been carried to them in the stable manure. It will be clear also that when the roots of crops spread themselves out over these differently charged soil granules, which are filled with and surrounded by moisture carrying the plant food, they are under the very best conditions to obtain and utilize it.

In order that there may be established a strong and deep granulation of the soil, the first essential condition is ample underdrainage, and it is most fortunate that, in the

great majority of fields, natural conditions abundantly secure this. The most universal condition, requiring attention on all soils, except in the very limited highly organic types, is a deep and abundant incorporation of organic matter in the soil. When the organic matter is deeply and abundantly distributed throughout the root zone, it acts as parting planes between the soil particles, which prevent them from running together during times when the soil is long over-saturated with water. At the same time, when shrinkage comes in times of drouth, the finely divided and well-distributed organic matter greatly favors the action of the surface films of water in drawing the small particles of soil together into bunches. One of the most important advantages of growing the grasses, like blue grass, timothy and redtop, in the rotation is that, through their immense number of roots closely threaded in among the soil particles, they greatly facilitate the bunching of the soil particles together. Such crops are much more helpful in this way than are the

clovers, whose great service lies in their power to increase the nitrogen content of the soil. The two types together, or in alternation, give the best and most enduring effects.

Winter weathering, naked summer fallowing, fall plowing and liming are other treatments which greatly influence soil structure.

CHAPTER II

PRINCIPLES GOVERNING THE PRODUCTIVE CAPACITY OF FIELDS

IT is my wish to say, in simple plain words, for the man who does things, why we do, what we do, when we do, either to maintain, to increase or to restore the productive capacity of our fields.

Even in fields of virgin soil there are wide differences in the ability to produce; in their capacity for endurance; and in their response to treatment. This is true when fields lie side by side, with identical conditions of climate and under the same crop, springing from the same lot of seed, planted at the same time and in the same way. Why is this so? When it comes to doing things there is nothing which contributes so much to dispatch, to certainty and to economy as a

thorough comprehension on the part of the doer of the why of doing.

To understand the whys of doing in soil management, we must have a clear notion of the nature of soil. The material of every field is composed largely of rock fragments, and differences between these rock fragments are responsible for many of the whys for doing what we must to secure the results desired.

In the surface four feet of an acre of moist, coarse, sandy soil there is spread out more than 45 square miles of water from which the root hairs of crops may draw their supply. But a good loam soil presents six times this amount, or 270 square miles, while our finest clay soils carry thirty times as much, or more than 1,300 square miles per acre of field. With feeding surfaces ranging from 45 to 270 to 1,300 square miles per acre, it is clear that there must be wide differences in the productive capacity of soils due to differences of internal surface alone, even when their chemical natures may be identical, and it must be very clear, too, that with

like tillage and similar fertilization, we can never hope to make the coarse, sandy soils equal the finer types in their ability to produce, except it be in the line of special crops. A very large internal soil surface, then, is one of the fundamental physical factors of a productive field. Potentially the coarse, sandy soils are the least productive, and the finest grained soils possess the highest possibilities, while the loamy types range all the way between the two extremes, in both their power of endurance and in their immediate producing capacity.

IMPORTANCE OF SOIL SURFACE

But why is it that these enormous soil surfaces are so fundamentally essential in determining the productive capacity of fields? First of all, it is so because only such large surfaces can retain a sufficient amount of water to last from one rain to another and meet the needs of rapid plant growth. The thickness of the layer of water left behind, held by the surfaces of the soil grains after

twenty-four hours of perfect drainage, is so extremely small that only something like four to six pounds of water per cubic foot of coarse, sandy soil can be retained. The loamy soils, on the other hand, having a much larger internal surface, are able to retain from 24 to 30 pounds; while the finest clay soils hold back as much as 35 to 40 pounds of water per cubic foot. The large differences in surface, therefore, determine fundamentally the differences in water-holding power which we find in different soil types, and this in turn influences their relative productive powers.

In the second place, the immediately available plant food carried by soils is largely contained in the soil water as sugar is dissolved in tea, and in this condition the root hairs of the crops imbibe it by absorption. This being true, it must be clear that those soils which can retain most water will also be able to retain most of the immediately available plant food material. So, too, when rain falls in sufficient amount to produce leaching, a much larger proportion of

the plant food held by the coarse, sandy soils must be lost in the drainage water, and for this reason the coarse soils cannot have the productive capacity of those possessing finer grains and a greater surface.

It will be clear also that you may much more safely apply larger amounts of fertilizers at one time to fine-grained soils than you can to the coarser ones without danger of its being wasted in leaching, and without danger of making the nutritive solution too strong. In other words, coarse-grained soils require the most frequent fertilization, but in smaller amounts at any one time. Besides this, in countries where the rainfall in the early part of the growing season is small, fertilizers may safely be applied in larger amounts than where early rains are excessive.

In the third place all of the plant food of crops, except carbon, nitrogen and water, which are derived from the air, must be dissolved out of the surfaces of soil grains. This being true, soils presenting the largest surface upon which the soil moisture may

act will yield phosphorus, potassium, calcium and magnesium both most rapidly and in largest amounts; and, just as the field in which nutritious grasses grow most rapidly makes the best pasture, so a soil with the largest surface, when other conditions are right, makes the most productive field. Just as the great increase of surface presented by powdered sugar and fine salt, over that of the rock candy and rock salt form, causes these to dissolve far more rapidly, so must the fine-grained, large-surfaced soils dissolve and yield plant food to crops far more rapidly than the coarse-grained ones can.

There is a fourth and extremely important function which the surfaces of soil grains have in determining the productive capacity of fields. It is that of concentrating the very soluble and immediately available plant food materials in the thinnest portion of the water films immediately about the soil grain surfaces and retaining them there with such power that it is only with much difficulty that they are leached away. If it were not for this property of

soils it would be necessary for us to apply fertilizers both more frequently and in larger quantities than we now do. We have found, for example, that after washing the cleanest coarse sand, which had been placed in a solution of so soluble a substance as saltpeter, ten times in twice its weight of distilled water, stirring the sand vigorously during three minutes each time before draining the water away, that this sand retained enough of the saltpeter to represent 244 pounds per acre in the surface four feet of such a soil; and this saltpeter contains both potash and nitrogen, two of the most important elements of plant food.

But how can a soil surface exert such a power? Your own personal experience will help you to understand this. A marble immersed in water and then withdrawn comes out wet; a layer of water is held firmly about it. Part of this water will drain away but there remains a portion which cannot be shaken off. If this layer of water is held so firmly by the marble as to be removed from the vessel with it, it must be clear that

this layer of water must move about in the water with the marble. Moreover, if the water were poured out of the basin, the film of water would remain on the marble and with it would stay any substance which might be dissolved in the water. So it is with the soil of the field. When a heavy rain comes which produces leaching, it finds the soil grains already invested with water films, and over these the fresh water simply slides, allowing much of the dissolved plant food to remain behind. When we use oil as a lubricant for machinery, we make a practical application of the same principle. Both the axle and its bearing are wet with the oil, and the two layers simply slide one over the other, and so firmly and rigidly do these two layers adhere to their respective surfaces that the metal faces are held apart and their wearing thus averted.

This firm retention of the soluble plant food materials about and upon the soil grain surfaces does not interfere with the plant roots feeding upon them, because the root hairs themselves become surrounded by

layers of the same solution, carrying the dissolved plant food. The surfaces of the one are brought alongside the surfaces of the other, and one and the same film overspreads both; and when heavy rains come this mutually investing film remains behind with its load of food materials. Some of this food material is of course lost, but it is through the much slower process of diffusion.

This brings me to consider a principle which underlies proper land drainage. It is very important that when rain falls upon a field the excess water remain only just long enough on its way through the open water passageways to saturate the soil. Anything longer than this provides time and opportunity for the most valuable plant food materials carried in the water films about the soil grains to diffuse out into the moving water and so become lost in the drainage. Thus we have an explanation of a seeming paradox, namely, that properly drained fields lose less of their soluble plant food by underdrainage than do those poorly drained.

This statement is in seeming contradiction to the common experience that open sandy soils are more leachy than are the loams and the clay types, and this leads me to the consideration of a second and most important physical factor which influences the productive capacity of fields.

SOIL STRUCTURE

In a clean sand each individual grain is a unit by itself, having but a chance position and relation to those with which it may come in contact. But in every highly fertile soil there is a marked structure. The individual grains are bunched and more or less rigidly bound into groups, granules or crumbs, causing the soil to appear more or less coarse grained and to behave somewhat like a sand in its manner of handling and in the movement of water and air through it. Even in potter's clay, before it has been tempered and is ready for the wheel, there is more or less of granular structure, which must be destroyed by puddling through

kneading or other means before a close, fine-grained and strong ware can be shaped from it.

The necessity for the crumb structure in all soils except the coarsest, sandy types is found in the fact that the open spaces through which water and air must move and into which roots, root hairs and soil organisms must penetrate in order to place themselves in contact with soil surfaces would be very much too narrow to admit of the necessary amount and rate of movement. An illustration will make this point clear; suppose we lay upon the table three balls, all of the same diameter and so that they touch one another, and then set on top of these a fourth, so that this one touches the other three. The open space left between the four balls may represent a pore space in any soil. The largest root which could pass through such a space without having its cylindrical form changed could have a diameter of only about 16-100ths of the diameter of the balls themselves; or, in the case of the soil particles, only .16 to .2 of the diameter of these

particles. But the mean effective diameter of the particles in our coarsest, sandy soils is such that some 200 of them must be placed in line to span a single inch. So the diameter of the root which could pass through the space between these grains, when all are in touch, could only be of the order of that possessed by a single cotton fiber, or about .001 of an inch. But in the average loam soil the diameter of the mean effective grain, after the dry soil has been broken down by rubbing in a mortar requires some 1,200, instead of 200, to span a linear inch, while with the finest clay soils as many as 6,000 grains are needed.

Small, then, as the pores are in our coarsest, sandy soils, those in the loams and in our finest clay types, if they did not possess the crumb structure, would be but one-sixth and one-thirtieth respectively of that stated for the coarsest, sandy soil. But another principle must be here stated to make more clear the immense importance of the granular structure in soils. It is this: The flow of water and of air through soils and sands in-

creases in the ratio of the squares of the effective diameters of the grains. That is to say, in the coarse, sandy soil, in the loams and in the fine clay types, if these did not have the crumb structure, the flow of air and of water through them would be in the order of 900 to 36 to 1, the movement through the sandy soil being 900 times more rapid than through the finest clay. If, for example, two and one-half hours were required to permit the coarse sandy soil to dispose of the excess water falling upon the field during a given rain, by underdrainage, the finest clay soil, without the granular structure, would require some three months to free itself of a like amount by underdrainage. It is therefore clear that the finest clay soils can only be surface drained until after they have acquired the crumb structure to a greater or less extent. More than this, in the properly open soil there are but two and one-half hours between rainfalls during which diffusion can carry the soluble plant food into the water draining away, while in the other condition this loss by drainage is continuous.

The low producing power, or absolute sterility, so invariably associated with puddled soils and with those too close in texture, we believe to be primarily due to a lack of available moisture, notwithstanding the seeming paradox that they are carrying an excess of it. It is a familiar fact that crops wilt and cease to grow in close-textured clayey soils when still carrying 8 to 12 per cent of water, while they may grow luxuriantly in coarse, sandy soils possessing but 1 to 3 per cent. So, too, we often find desert types of vegetation growing in humid climates on extremely close-grained clayey soils, and more strangely still in peat swamps where the water content is excessively high. To understand these facts it must be remembered that there is a certain thickness of water film which is held so firmly to the soil grain surfaces as to be wholly unavailable to the crop. Portions of this layer cannot be driven off completely even at the temperature of boiling water. When all of the facts shall have been worked out, we believe it will be found that

the thickness of the unavailable water about the surface of the soil grains is essentially the same whether these be large, as in the coarse, sandy types, or very small, as in the finest clays; and if this is the case the absolute amount of unavailable water must increase as the internal surface of the soil becomes greater and as the diameters of the soil particles decrease.

The coarse, sandy soils, with their relatively small internal surface, carry a correspondingly small amount of unavailable water, and hence in them small rainfalls in dry times have a relatively high efficiency. So, too, must soluble plant food and fertilizers, when applied to them, for the same reason, have a relatively high efficiency. But in the finest clay soils, especially if they are not strongly granulated, the amount of unavailable water is very large, and hence it is that heavier rainfall during drouth periods and more liberal applications of fertilizers are required to produce the same relative increase. But it is possible to have the finest clay soils so completely puddled

or separated into their ultimate grains, and the effective soil surface thereby so enormously increased, by the minuteness of the particles, that nearly the whole of the water, even when the soil is saturated, becomes unavailable to plants and for the simple reason that the water films are too thin and therefore too strongly held to be removed. From the standpoint of plant function we have the paradoxical condition of a sandy soil, containing perhaps 1 per cent of water, being effectively more moist than a puddled clay soil containing 20 to 30 per cent, or than a peaty soil containing perhaps 40 to 50 per cent.

But when the finest clay soils are put into a highly granular condition, with the kernels having the order of coarseness of the sandy soils, these compound grains may themselves become invested with water films which are thick and therefore available to crops. By such a change of structure, therefore, the clay soils not only retain their enormous surfaces, carrying water in which plant food may develop and accumulate, but

by the bunching of the fine particles there has been superadded to the already enormous surface an additional large area which now is able to retain much water in available form and so advantageously placed that the plant food from the moisture within the soil kernel can diffuse out into the available film and thus also become available to the crop.

Tilth, or the physical condition of the soil, then, must be of very great importance in determining the productive capacity of fields, first of all because it limits the availability of this soil moisture, and through this, at the same time, the availability of the plant food itself. Without the coarse-grained texture and openness of structure there must be imperfect drainage, inadequate soil ventilation and lack of freedom of movement and of room for the proper development of either the roots of crops or the multitudes of soil organisms whose activity is so indispensable to the maintenance of soil fertility.

DEVELOPMENT AND MAINTENANCE OF SOIL STRUCTURE

But how is this important structure developed in a field? How can it best be maintained? In what ways may it be destroyed or rendered less complete? The alternate drying and wetting, causing shrinkage cracks, followed again by expansion when water is absorbed, is nature's most universal agency for developing crumb structure. In climates where the ground freezes the soil moisture is concentrated into irregular crystalline masses which, by their strong expansion as the water freezes, force the soil apart in many irregular ways, thus creating open spaces when the ice again melts. This freezing and necessary expansion heaves the surface of fields bodily, placing them at a higher level and leaving the soil in the spring to a corresponding extent more open. Then the roots of crops, by their wide ramification and great expansive power resulting from increase in diameter as they grow, and by the drying of the deeper soil as they with-

draw water from the lower depths, tend strongly to open passageways and thus develop crumb structure. The action of earthworms, ants and other burrowing insects and animals constitutes another class of agencies tending to develop and maintain in soils their much needed openness of structure.

But in order that these factors may be most efficient in developing structure it is imperative that there shall be maintained, at all times and throughout the whole root zone, a high content of humus and organic matter. This organic matter is of first importance from the standpoint of developing immediately available plant food, but it has the highest value also in developing and maintaining the important physical character of crumb structure. This is so for the reason that however parting planes, openings or fractures in the soil may be formed, dividing it into blocks and crumbs, the humus and organic matter tend to fall into the openings between the blocks and crumbs, thus forming a lining for the separate faces, which tends strongly to prevent

the soil from again uniting into an adhesive mass. In this manner the soil becomes deeply mellow, easy to work, very much less liable to wash and far more productive.

For ordinary field conditions this incorporation of organic matter must be secured through deep plowing, which aims to turn under all waste refuse and occasionally green and stable manures. Going with this practice there must be an intelligent rotation of crops, which includes the legumes, to accumulate nitrogen from the air and to fix it deeply in the soil in their tubercle and root growth; which includes the grasses having dense root systems, tending to both deeply and finely divide the soil by the close ramification of their roots and to make the granules so formed more rigid by the cementing action of substances rendered soluble by the carbonic acid transpired through their roots and which accumulate in the granules by diffusion, to become precipitated there as the soil is deeply and thoroughly dried by the action of the roots in supplying the plants with water. The

cereal, vegetable, fiber and sugar crops exert but a feeble structure-building effect upon the soil. They tend rather to weaken soil structure by the removal of the soluble plant food ingredients which have accumulated there, thus rendering it both structurally defective and deficient in immediately available plant food. These last crops, therefore, make chiefly the financial earnings, while the grasses and legumes are largely restorative, but may be earning crops as well. It must be remembered, however, that their restorative effect lies wholly in their power to mend the structure and in adding the single element nitrogen to the soil. Other plant food elements they never add, but may, to some extent, help to make them more available and thus permit larger yields to follow them, but whose removal, when no return is made to the soil, hastens its ultimate exhaustion.

When once the soil becomes deeply charged with organic matter its decay liberates carbonic acid in large volumes, and this in turn is a very material solvent for plant

food elements, especially for lime; and, with an abundance of lime carbonate in the soil, this tends to neutralize the nitric acid formed during the processes of nitrification, thus keeping the soil from becoming sour and allowing the nitrates to be produced in much greater amounts, keeping up the nitrogen supply for the crop on the ground. But this is not all. The action of lime in solution has a strong tendency to flocculate the soil, not only throwing it into bunches but tending to give firmness to the granules, rendering them less easily broken down by the action of rains, so that this is one of the ways in which a high content of organic matter in the soil tends to prevent washing.

There is no portion of the United States in which the productive capacity of fields is so much reduced by surface washing as in a wide belt extending through the South Atlantic and Gulf states. This injury is due primarily to inadequate underdrainage. The lack of effective underdrainage is in turn due to insufficient granular structure in both soil and subsoil, to the heavy char-

acter of the rainfall and to the small slope of much of the surface. The lack of proper granular structure is due to a general deficiency of lime and to a failure to thoroughly and deeply incorporate and maintain in the soil a high content of organic matter. The absence of deep winter freezing of the soil, the low content of lime in much of the underlying rock, and the heavier rainfall make the problem of maintaining a proper soil structure in the South much more difficult than in the North. But very much more can be done than has been generally attempted toward improvement along these lines. More frequent and deeper plowing, a more persistent effort at turning under roughage and green manures, the maintenance of more live stock, and the adoption of rotations which shall secure the effect of deep root action, so soon as underdrainage has been secured, are the fundamental lines along which the productive capacity of these fields must be built up. Mineral fertilizers are now and will continue to be needed, but their efficiency will be increased a hundred-

fold when the improvements along the lines suggested have gone before.

Composition, first, and structure, second, are the master factors which determine the productive capacity of fields. Let me illustrate through the practice of composting soils preparatory to their use on the benches of forcing houses. With the practical man his first choice is a rich sod, his second a rich mellow loam. To the soil he adds from a third to a half its volume of good stable manure, perhaps supplemented with phosphates, lime and potash. The whole is thoroughly mixed, put in good moisture condition and given opportunity for fermentation under conditions of frequent turning. By this treatment he secures a soil whose structure is ideal and which is at the same time carrying a heavy charge of plant food in highly available form. A strong blue grass or timothy sod is itself a guaranty of thorough and strong crumb structure. Because the volume of the soil is small, it is imperative that the root system be brought into effective contact with the whole of it, that

the available surface shall be as large as possible and that the soil with which the roots come in contact should be heavily charged with essential plant food. The decay of the manure in contact with the soil grains leads to their becoming highly charged with plant food in water-soluble form. Quite likely, too, at the time of planting, the manure and other substances will be supplemented by sodium nitrate.

The soils of Florida and the black, fertile soils of the Northwest are both of them sufficiently open, well drained and well aerated, but there is a profound difference between them which makes it possible for the black fertile soils to carry very much more readily soluble plant food materials than can be stored in the Florida type, so that were they placed side by side under identical climatical conditions, there is hardly a possibility of making them commercially equally productive. As a matter of fact there is a great difference between the amounts of available, water-soluble plant food materials carried by like volumes of the two soils, and it is in

this fact primarily that their great difference in power of production lies.

We need to remember that it is hardly possible to wipe any surface dry, neither is it possible for a root hair to withdraw all of the water from the surface of a soil grain. This being true, the soils which have an enormous surface to which the water may adhere must carry a correspondingly large amount of water which no crop can ever use, and so it happens that a fine-grained but well-granulated soil may carry 10 times the amount of water which a coarse, sandy soil will carry and yet be actually drier, so far as being able to meet the needs of crops is concerned, than is the sandy soil with its much less absolute amount of water. Now, if this is true for the water, it must be equally true for the water-soluble plant food materials, and so it may happen many times that a small amount of fertilizer applied to a sandy soil, with its small surface and high per cent of available water, will be relatively more effective than in the case of the finer soil with its larger surface. But it

will be easy to comprehend that the fine-grained but highly granulated black prairie soils of the Northwest can carry and do carry on the interior of the granules large amounts of soluble plant food materials for which there is no possible room in the coarse, sandy soil, and so the productive capacity of such a soil can easily be much greater than those of the Florida type, and when the internal soil surface is so large and it is highly granulated so that it must carry in soluble form more material than is required by a dozen crops in order to be able to supply the plant food elements as rapidly as one crop can use them, then such a soil must decrease in productive power whenever any one of the essential food elements cannot be delivered to the crop as rapidly as needed, even though there may be present in the soil enough for many such crops.

Perhaps I can make this thought clearer by an illustration. Suppose you have a three-horse tread-power which is in such a condition that when one horse is placed in it the resistance is too great for any work to

be done; when you put in the second horse suppose one-half its weight is also required to overcome the resistance. You then from two horsepower get an efficiency of but one-half horsepower. But when you put in the third horse you realize its full efficiency and get one and a half horsepower, or three times as much as you were able to realize from two horsepower. So it is with the soil; with a given amount of soluble plant food present—and this may be two or three times that required for a given crop—you may yet be unable to realize from it; while, adding a comparatively small amount more, you may realize the full efficiency of this additional amount.

CHAPTER III

FUNCTIONS, AVAILABILITY AND CONSERVATION OF SOIL MOISTURE IN CROP PRODUCTION*

THE problems of soil moisture, as regards crop production, are a complex of many factors, some of which are physical, some chemical and others biological. These factors are quantitatively and qualitatively subject to wide variations as they are brought into interaction; this being true, the resultants expressed in crop yields, both as to quantity and quality, must necessarily be extremely variable. Confronted with such conditions in our research work, we came

*Prepared by Mr. King while in China, to be read before the agricultural subsection of the British Association for the Advancement of Science at their meeting in Winnipeg in August, 1909. In his introduction, thanking the Association for the invitation to prepare the paper, he says, "I regret exceedingly that, being far away from all my notes and literature, I shall not be able to be as explicit as you may desire or as I would like to be."

early to realize that interactions which, for the time, seemed to have been chaotic might after all be found to have occurred along lines of perfect order when all the reacting factors were known as to their intensity, duration and application. It is of the highest importance in agricultural research work and for agriculturists to recognize and to keep vividly before the mind, when interpreting crop yields, that these are always resultants of complexes of factors which we are only beginning to know and beginning to learn how to deal with experimentally. In a discussion of soil moisture problems from the standpoint of soil physics, as has been requested, I cannot hope to do so intelligibly or profitably without properly articulating its factors with those others between which interaction always occurs in crop production.

In the semi-arid and arid sections of Canada, as in those corresponding in the United States, the duty, conservation and availability of soil moisture are of vital industrial interest, but scarcely more so than

they should be in almost every agricultural district on the globe; for it is doubtful if there are agricultural soils to be found anywhere under existing climatic conditions where, in the majority of seasons, deficiency of available moisture must not become a marked limiting factor of yield. In stating this general conclusion to which my own research work and that of others have led me, it is always to be understood that sound seed of high vigor, good physical and climatic conditions, abundance of available plant food and good management coexist, and that when they do, almost without exception, deficiency of available soil moisture must come to be the limiting factor of yield where supplemental irrigation is not practiced. And now that I am writing from perhaps some of the oldest agricultural fields in the world, studying these stupendous interlacing systems of canalization which are at once means of travel, of land drainage, of irrigation and, in a high degree, conservators of soil fertility; and when I see how each individual field is laid out so

as to retain upon its face the maximum percentage of the rainfall, so that any excess that must leave the field does so with an absolute minimum of velocity and so that even a share of this may be impounded in reservoirs to evaporate or to be used for irrigation, while its soluble plant food, the finest silt and organic matter, are put back upon the fields in the form of mud dressings, and all of this too, in the most humid parts of China, I see no reason to modify the conclusion just stated; but I have been much humiliated to find that some of my brightest and most original ideas are here worked out in far greater detail and that they have been practiced for perhaps thousands of years by millions of men behind the old wooden plow —a plow which I have now seen completely reverse the furrow slice and cover out of sight herbage of considerable length.

That sufficient available moisture, present at all times in the soil, must be of prime importance in crop yields is made clear by stating that not only is it, by weight, the largest food substance entering the living

plant, but it is an indispensable medium in the soil in which all other plant food derived from the soil is elaborated and by which it is conveyed to and through the plant tissues. In my own research, corroborated by others, it has been shown that our ordinary agricultural crops, in coming to maturity, withdraw from the soil, including that lost by evaporation directly from the soil, from more than 250 tons of water to more than 600 tons for each ton of water-free substance produced in stem, leaves and fruit. It is a matter of first importance in laying out and developing plans for what has been designated "dry farming" to know what minimum losses under such conditions may be. I am not able to give reliable data as to the ratio of water withdrawn from the soil through the crop to that lost through the soil itself, but it is my judgment that the necessary losses in good yields cannot fall below 200 to 400 tons per ton of water-free produce. I think there is little reason to doubt that under semi-arid conditions crops may be somewhat more economical in the use

of water than they are in humid climates, but it appears to me very doubtful that they can become as much more so as some have been led to hope and believe. Beside my direct experimental results which support this conclusion, we have to consider the fact that the process of physical diffusion appears to be entirely too slow to supply the plant with its essential food substances from the soil, and I feel that we shall come to find that strong transpiration is a necessary condition for rapid growth, although opposite views are held by some.

From the best available data it appears that to produce yields of 12 bushels of wheat and 20 bushels of barley per acre there must be lost from the soil between spring and harvest not less than 3.6 and 4.28 inches of water respectively, and there must be left in the soil at harvest enough water for growth not to have been stopped.

It is a fact of great practical significance, too, that the necessary transpiration of moisture through the crop is far larger than the evaporation from the dry soil surface and

that this loss is entirely beyond control. We may materially conserve soil moisture by methods of tillage, but we cannot hope to reduce the loss through the crop itself. Another fact of the greatest importance to keep in mind in developing "dry farming" methods is that there is a tendency for variations in the amount of rainfall to run in cycles of years. In the United States we have been passing through a series of years of greater rainfall for portions of our semi-arid region than is usual, and to this fact is due in great measure the large yields which have been secured in many, if not in most, cases. I have in mind a bulletin issued by one of our experiment stations, giving the yields of crops under the conditions of "dry farming," but when the actual rainfall of the growing season for the district in question was compared with that at Madison, Wisconsin, it was found that, both in amount and in distribution, the rainfall producing the crop yield given was equal to those giving good yields in Wisconsin, which is in no sense a "dry farming" state.

I would not say anything to discourage rational effort toward bringing semi-arid lands under cultivation, but it is important that the fundamental difficulties be understood and that the lines of attack should be shaped accordingly. Dire disaster has come to many farmers in our country, and it will come to many more if these facts are not recognized and acted upon wisely. Provision must be made to tide over years of drouth which are certain to be experienced at longer or shorter intervals.

The physical condition of a soil exerts a profound influence upon the absolute amount of moisture it may retain; upon the amount of water which may become available to the crop and to the micro-organisms in the soil; upon the elaboration of plant food in the soil; upon the movements of plant food and the development of root systems in the soil; upon the retention in and loss of immediately available plant food from the soil; and upon the movements of both water and air in the soil; and so a chemically rich soil may be one of extreme

sterility, as may a physically perfect soil be equally barren.

There are but few agricultural soils, no matter how productive, that would not be ruined for the time if they were to be separated into the single separate ultimate grains of which they are composed. The ability to retain capillary and fixed water would thereby be greatly increased, but the amount of water available to crops might, in some soils, be reduced nearly to zero; and in a full understanding of these facts is to be found the explanation of the important part played by the physical condition in determining the productive capacity of a soil which is chemically rich. Soils may be climatically poor, physically poor, chemically poor or biologically poor and vice versa; and an adequate rational soil management can only be expected to follow a full understanding of the principles underlying these conditions and a knowledge of the mutual interactions which result from good and from faulty practice.

It is a matter of common knowledge that

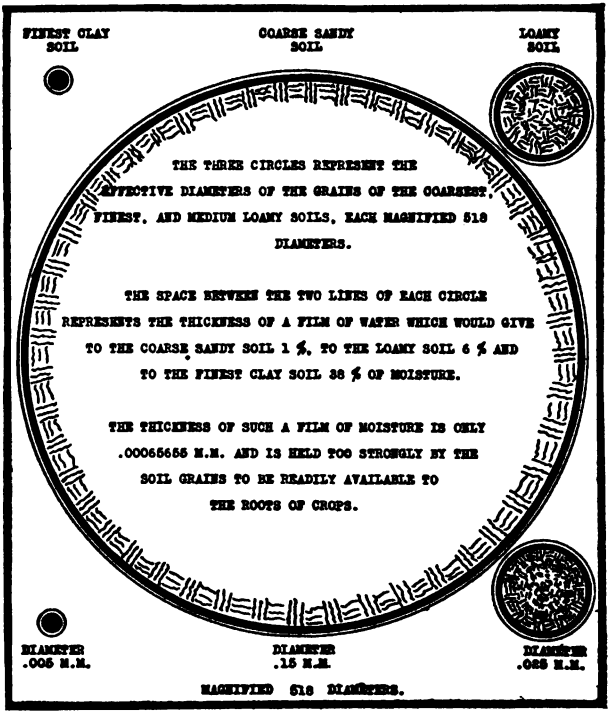
only a portion of the moisture present in a soil is available to a crop; that a larger per cent may be available to one crop than to another; and that a soil whose ultimate grains are large may be more completely exhausted of its moisture by a crop in times of drouth than can be the case where the ultimate particles are much more minute. It is a matter of practical experience, too, that smaller applications of fertilizers applied to one soil will bring a greater measured response from a crop than will a like dressing applied to another soil bearing the same crop, and that soils differ widely in their ability to retain fertilizers against leaching. These and many other differences in soils I have come to think of as associated with, and in a considerable measure due, perhaps primarily, to differences in their physical conditions; and we shall state here briefly, by way of suggestion to investigators, the lines along which we have been looking for an adequate explanation of these differences and for a basis in principle for good practice in soil management.

It is a fact that soil particles, in common with other solids, retain a film of moisture about their surfaces with an intensity which the roots of plants are unable to overcome and which can only be removed by high temperatures or other means. The thickness of these films is unknown, but varies with the intensity of the removing force and perhaps with the size and character of the soil particle. Down to a certain thickness water will be sheared off these films by gravity more or less rapidly; down to a less thickness the films may be thinned by surface tension and capillarity; beyond this limit we have the *fixed water* which in all highly fertile soils I believe to be strongly charged with plant food, more so than the gravitational layer and than the capillary layer. I am hoping that research may experimentally fix the limits of these thicknesses of films and the variations and nature of the solution concentrations in them. In the meantime, as a first approximation, I am thinking of the *fixed films* as practically uniform in thickness over the surface of all

sizes and kinds of soil grains and over those of root hairs and micro-organisms inhabiting the soil moisture.

It seems to me likely that the absolute thickness of the fixed film may be greatest on the smallest particles of a given kind, but if all surfaces carry fixed films of the same thickness it is clear that the per cent of unavailable moisture carried by a soil must increase as the diameter of the individual particles decreases, and, if so, we have in this an explanation of why a crop may thrive in a coarse, sandy soil containing 1.5 per cent of moisture when the same crop will wilt in a clay soil when its moisture content may be as high as 8 per cent; when the sandy soil, weighing 100 pounds per cubic foot, carries 1.5 pounds of water, while the clay soil, weighing 70 pounds, carries 5.6 pounds of water per cubic foot, or nearly four times the absolute quantity per acre of field and foot of depth, one carrying the equivalent of less than .29 inch of available water, while the other carries more than an inch per foot of depth. On the coarse sandy

soil .3 of an inch of rain would double the water content of the surface foot and place



it in good growing condition, while in the clay soil the same rainfall would be largely retained near the surface, above the roots,

and be quickly lost by surface evaporation from the soil itself. On the sandy soil the rain would have dissolved any soluble salts accumulated near the surface and have carried them down about the surfaces of the active root hairs, so that the crop would have been fertilized as well as watered. On the clay soil the water might even have the effect of strengthening the upward capillary rise from below, leaving the deeper soil both drier and less richly charged with soluble plant food than before.

Because of these differences of surface, too, I think of the coarse, sandy soil as less able to retain available plant food upon its grains in the fixed water and, therefore, more liable to lose it by leaching, while at the same time a smaller application of fertilizer will be able to effect a given increase in yield than can be the case with the clay soil with its much larger surface and greater quantity of fixed water. Our experiments have demonstrated that clean, coarse sand may retain in the fixed water films, against ten repeated washings in distilled water, large

quantities of potassium nitrate which, however, was recovered by suitable methods, so that, without doubt, soils do have the power to retain, against leaching, soluble salts in purely physical solution within the *fixed water* about the soil grain surfaces. But when the root hairs of plants place themselves alongside these fixed water films and the two films join, we have the necessary physical conditions for the transfer by diffusion of the soluble plant food, carried in the fixed films, over to the plant. It is thus easy to see that profound differences, purely physical, may exist between the large simple grains of the coarse, sandy soil and the compound granules made up of multitudes of smaller ones in the well-granulated fine clay soil in good tilth.

When, by bad management, a fine clay soil is injured in texture by puddling, by breaking down the compound grain structure which has given to it a texture more nearly like that of the coarse, sandy soil, every fine particle torn out of contact in the compound grain is now able to appropriate

Fig. 9—Tea bushes with the ground mulched with straw. Japan.

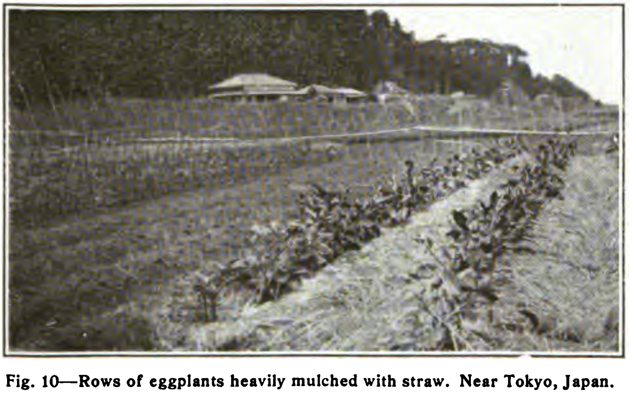


Fig. 10—Rows of eggplants heavily mulched with straw. Near Tokyo, Japan.

Fig. 17—Irrigated lands in the citrus belt of southern California.

its full volume of fixed water, taking it from the available or capillary supply, and it will be clear that if the soil has its free surface thus sufficiently increased so that all the capillary water becomes fixed it may thus have been rendered *physiologically dry,* without absolute loss of water.

Proper soil texture, therefore, having now in mind the one factor of water supply to the crop, as water only, is a very important consideration. In the case of "dry farming" that soil whose internal surface in the effective root zone is just large enough to retain the season's rainfall against gravity and downward capillarity will be able to utilize the rainfall to best advantage, and any management which seriously alters this physical condition must have the effect of reducing the yield when available moisture is the limiting factor.

In humid climates drouthy conditions often prevail in peat soils and certain clay types, especially when the subsoil near the surface is extremely fine in texture, when on surrounding soils of different texture, and

with smaller absolute water content, good growing conditions exist, because these soils are *physiologically* more moist, although they may contain absolutely less water. In our peat soils the extent of solid surface for *fixing* water is extremely large, and hence we often see desert types of vegetation growing in such places. It is my judgment, too, that any soil containing a high content of colloidal material must for that reason have a high percentage of unavailable water, each colloidal particle having the power of rendering *fixed* its full quota of water.* And if it shall be found that colloid substances in soil moisture have the power of rendering a portion of it unavailable to crops because of the *fixed* water carried by the particles, then we may expect that even salts in solution may operate similarly, plants wilting in them when their content of salt is so high that the power of these molecules to *fix* water is great enough to per-

*On the Suspension of Solids in Fluids and the Nature of Colloids and Solutions, by F. H. King, in Vol. XVI, Part I, p. 275, Trans. Wis. Academy of Science, Arts and Letters, 1908.

mit water to be withdrawn from the tissues of the plant to meet the demand.

But the rate of growth of crops must decrease in a given soil, when water is the limiting factor, long before the water content of the soil has been reduced to the *fixed* quantity; indeed, so soon as the point of optimum amount has been passed. When a root hair has placed itself alongside a series of soil granules the capillary water comes to invest it in common with the soil grains, so that as moisture is imbibed, by whatever process or mechanism, the capillary equilibrium must be destroyed and a flow toward the root hair established. This flow would be maintained so long as the surface tension about the root hair was able to supply the loss created by imbibition. But the rate of supply would decrease as the capillary films thinned out, and a point would be reached when the rate of growth would slacken for lack of a sufficiently rapid water supply, and stop altogether when the root hair became powerless to draw more water upon itself.

There are reasons for suspecting that a re-

lation may be found to exist between the diameters of the root hairs or absorbing bodies and of the soil grains or granules, or possibly between relative surface tensions caused in other ways, so that one crop may be better adapted to feed from one type of soil than another crop is. At any rate there is some way, either by reason of extent, size or character of absorbing surface, whereby the oat crop, for example, withdraws water from a soil faster and more completely than the barley crop is able to do.

It is doubtful if any condition of soil contributes more toward permitting a large yield being associated with a low water content than does that of great depth, which permits the placing of root hairs in the best capillary connection with the greatest volume of soil. Where the textural conditions of the subsoil are uncongenial and a large root surface is forced to be developed in a small volume of soil the demands of the plant for moisture may become so large that the rate of removal from the soil exceeds the ability of capillarity to bring it. The soil

will then become dry about the root hairs, thus cutting the plant off from further moisture and with it food supply. In many of our coastal plains southern soils, where the roots are forced to develop near the surface on account of the bad textural condition of the subsoil, drouth conditions often prevail with a high water content in the soil less than 18 inches below the surface. It is a fortunate circumstance that deep congenial subsoils are generally characteristic of semi-arid and arid regions, so that the root systems of crops may there have deep as well as broad pasturage in those soils, and upon this feature more largely than any other must the hope of "dry farming" rest.

Earth mulches may be very material conservators of soil moisture, but the advantageous use of them requires a thorough understanding of their nature and good judgment in their application. Air-dry soil, whether firm or loose, is an excellent mulch. When loosened in such a way that many large non-capillary spaces are developed soil becomes the most efficient mulch. It is

not sufficiently appreciated, however, that the mulch is so much soil taken out of active service, and that it only conserves moisture already in the ground, adding practically nothing to the supply existing before the mulch was developed. It needs to be understood, too, that a deep mulch maintained during a season of small intermittent rains may waste more moisture than is saved, on account of the fact that small rainfalls are wholly retained in the upper layers of the mulch and lost directly and completely to the air, whereas if the mulch had been thin enough to wet through, capillarity would draw a portion of the rain directly downward into the undisturbed soil to render effective service when conserved by subsequent restoration of the mulch. In regions where there is little or no rainfall after the mulch is developed it may with advantage be deeper, if this does not entail too great a loss by throwing out of active use the large volume of dry soil. In humid climates little will be gained, everything considered, by stirring the soil to a depth of more than two

to three inches. Repetitions of stirring must be determined upon by inspection to see whether or not the mulch is becoming especially damp by capillary rise from below or whether it has been compacted by wetting with rain.

In the case of all hoed crops, like maize and potatoes, it is easy to utilize soil mulches as conservators of soil moisture to the highest extent; but with the cereals, like wheat, oats and barley, modified forms of culture will have to be adopted in "dry farming" if much good is to be derived from mulch conservation. I believe it may be found practicable to adopt a method of cultivation for these grains that might be remunerative in the drier seasons by sowing the grain in bands two feet wide, leaving the same width of strips naked and alternating with the grain, which may be cultivated as often as desirable up to the time the grain is filling. In sowing the next year the strips naked this year should bear the crop and the cropped strips be left fallow. In this way advantage could be taken of the effect of both cultiva-

tion and naked fallow to develop plant food and conserve moisture, and a portion could be used by the crop each year, growing as it would immediately adjacent to the fallow ground. One difficulty in interpreting results from small plots with cultivated paths between is the fact that these paths contribute both moisture and plant food in sufficient quantity, even in humid climates like Wisconsin, to so affect the growth as to make the difference along the path not only measurable but distinctly observable by the eye. It appears to me that a system of culture worked out along such lines has more of promise than that of leaving the land entirely fallow on alternate years.

Where the grain covers the ground closely it is sometimes practicable to restore an earth mulch on the field after the grain is up, but seldom to advantage more than once, and this early in the season. Early plowing after the harvest, for dry regions, is to be recommended unless the ground is so extremely dry as to prevent the growth of weeds.

Where fields are fitted in the spring for either early or late crops, and especially the latter, the fitting should be done as soon as practicable, because in so doing not only are you conserving moisture, but you are developing available plant food at the most opportune time. Under humid conditions, if the field may lie several weeks before planting, and if the soil has been in good condition for plowing, it is better not to follow the plow with a smoothing, first, because it will lessen the effect of the soil as a mulch and, second, if the weeds have time to start, the harrow can more easily destroy them and develop an effective mulch when it needs to be renewed. Fall plowing, where there are winters, is an excellent conservator of soil moisture, especially where snows have a tendency to blow off, as the roughness tends to hold the snow, and the bright sun often melts it and permits it to enter the soil more readily. Where conservation of moisture is a matter of great importance such fall-plowed fields should be stirred as soon as possible in the spring by some fairly deep-

stirring tool, like our disk harrows. It needs to be remembered that there is no time when water is lost so rapidly by evaporation from the surface as when the soil is wet and naked. Then water may be lost at the rate of one to three pounds per square foot per day. Even a light mulch such as can be made by the light broad harrow, if the surface is uneven and the soil fairly mellow, will save an immense amount of water at such critical times.

In seeding, under semi-arid conditions, it is important to have the seed in contact with the soil which is in the best capillary connection with the undisturbed soil below, and the principle utilized by our various drills is thoroughly sound, especially where the press wheel to firm the soil directly above the seed, and then the light harrow, or its equivalent, follows to lay a loose blanket of earth over the press wheel track. It may sometimes be necessary to firm the surface to make a good capillary connection, which may have been broken, but if so a light harrow should follow the roller to restore a mulch at once.

CHAPTER IV

SOIL MOISTURE AND PLANT FEEDING

SOIL moisture in abundance, continuously maintained, is an indispensable factor in the growth of every crop. It constitutes from 70 to 90 per cent of the actively growing part of every plant. Through the action of light in the green of leaf, water entering from the soil and carbon dioxide entering from the air react to produce the largest part of all the dry substances of plants. No plant food in the soil is available to the crop until it is dissolved in the soil moisture, and through its solvent action and its movement through the plant, water conveys all plant food to the tissues and distributes it to the growing parts. It is not strange, therefore, that the right amount of water in the soil is so important a factor in the production of large yields.

But, important and large as is the part

water plays in crop production, it is powerless to produce results if other essential factors are absent or are not sufficiently abundant. When phosphorus, potassium, nitrogen, or any other essential plant food element is deficient in the soil, an abundance of soil moisture will make the largest crop possible under such conditions, but not as large as it could have been had other plant foods been abundant. On the other hand it matters not how plentiful other plant food substances may be in the soil, the crop must be limited by the amount of available water. When all plant food substances are continuously abundant, the size of the crop is limited by the number of plants and their ability to feed and grow.

In our 10-year measurements of the amount of water used by crops it was found that in average round numbers about 450 pounds of water must be taken from the soil and most of it passed through the crop for each pound of dry substance produced above ground. With good soil conditions and an abundance of plant food it was possible to

secure yields from ordinary crops of six tons of dry substance per acre. Six tons of dry substance means 24 tons of sugar beets and tops; it means 7 tons of hay containing 15 per cent moisture; 92 bushels of wheat and straw, and 756 bushels of potatoes per acre. These are large yields, but nevertheless possible and practicable under intensive cultural methods where there is maintained an abundance of plant food and soil moisture. But the right amount of moisture means about 4 inches of effective rainfall for each ton of dry substance produced, or 24 inches during the growing season. We get less than this, and it is not distributed so as to be most effective.

In China and Japan, where they must raise large crops every year or starve, they have been compelled to irrigate, although they have a larger summer rainfall than we. More than half of the cultivated lands of Japan are irrigated every year, but they also fertilize highly, applying, on the average, from three to five tons of manure in some form per acre every year.

We do not sufficiently appreciate in our practice that to double the crop on the ground we must at the same time double the crop feeding. This means that the soil must turn over to the crop double the amount of nitrogen, phosphorus and potassium, and that double the amount of soil moisture must be taken up by and passed through the crop. Abundant harvests occur only where there is abundant moisture and abundant food at the time when the crop does its most rapid feeding and most rapid growing. If either soil moisture or accessible plant food, or both, are deficient at the critical period a reduced harvest is inevitable. The Chinese and Japanese, working always small areas, watch these critical periods with the greatest care, and whatever may be deficient they make a desperate effort to supply at just the right time.

Then, where large yields are expected, it is very important to understand that less water is required for a crop, in proportion to the yield, when the soil is abundantly rich. We found that when in abundantly rich soils

corn, oats and potatoes used an average of 355 pounds of water for each pound of dry product; on the same soils, after they had become impoverished by repeated cropping without fertilization, the same crops used an average of 625 pounds of water for each pound of dry produce.

It is also true that a continuous abundance of soil moisture will permit a soil poor in other plant food to produce the largest possible yields for such soils, and from this it follows that, where there is an especially rich soil, an abundance of soil moisture is extremely desirable, and that where the soil is poor it is doubly important that the soil moisture should be kept at the best amount.

Where all plant food substances are in great abundance in the soil the yields are almost exactly in proportion to the amount of moisture which can be supplied to the soil without making it too wet. Thus we found, in our trials, that corn gave a yield of 11,000 pounds of dry substance; oats 8,000 pounds, and potatoes 7,000 pounds per acre when it was given but 2 inches of water more than

that contained in the surface four feet of soil at planting time, when it contained the best amount for growth; but under identically the same soil conditions, except that the soil moisture was kept constantly at the quantity for best growing conditions, the corn produced 16,000 pounds per acre, instead of 11,000; the oats produced 18,000 pounds instead of 8,000; and the potatoes produced 12,000 pounds instead of 7,000. But the amount of water used per pound of dry substance produced was very nearly the same in both cases.

With a combination of high fertilization and complete control of soil moisture it is practicable for market gardeners to increase their yields per acre by planting closer on the ground than is the usual practice, and this has long been regularly done in China and Japan. We found potatoes for the early market planted in rows one foot apart and the hills in the rows less than this distance. String beans are similarly planted, and cucumbers are grown in rows 28 inches apart, with a plant every 8 to 12 inches in

the row, the vines being trained on trellises. But these practices would be entirely impossible without high fertilization and a complete control of soil moisture.

In our trials with cabbage, on soil only moderately fertilized, where the plants were set 30 inches apart each way, the yield of dressed heads per acre was 15.3 tons; but where planted 30 inches by 15 inches the yield was 23.3 tons per acre of marketable heads, and the total green weight of crop in the two cases exceeded 39 and 59 tons respectively.

There is still another great possibility of increasing the annual returns in market gardening, where there is complete control of soil moisture, and this is in the growing of multiple crops, a practice long and generally observed in China and Japan.

We found in the province of Nara, Japan, the farmers following a rotation practice covering five or six years, in which they grow four or five consecutive crops of rice, yielding 59 bushels per acre, worth $90. After harvesting the rice the ground is fitted

and planted with barley in November, always in rows and usually in hills in the row. Early the next spring soy beans are planted between the barley rows. When the barley is harvested its usual yield is 55 bushels per acre, worth $36. The soy beans are cut green as a fertilizer for the following rice crop, the usual yield being between five and six tons per acre. After the fourth or fifth year of this rotation the ground is planted to melons or some other garden vegetable, from which they realize $160 per acre. They are thus realizing from a general farm practice a yearly earning of between $126 and $160 per acre, but this would be impossible without their practice of high fertilization and irrigation, notwithstanding they have a larger summer rainfall than occurs in the eastern United States.

These lines of advance in agricultural practice must become more and more important in the United States as the country grows older and more populous, and hence it is very important that our nation, in laying plans for the development and conserva-

tion of our water resources, should include agricultural interests in its policy, with a view to securing perfect land drainage and supplemental irrigation in the eastern part of the United States, where the questions will come to be of far greater importance to the nation as a whole than they ever can be in the West where water for irrigation is so limited.

When we shall have learned and acquired the habit of maintaining in our soils all of the plant food which a maximum stand of the crop on the ground can utilize, then water, if only supplied in the form of direct rainfall, will always be the limiting factor of yield, and we shall never be able to reap, year by year, the largest harvests until we arrange to supplement the rainfall at critical periods.

There is, however, great room for improvement in the methods of soil management aiming to better conserve and utilize the rainfall we do get. Here is where growers must begin, and must continue, where water to supplement the rainfall is not avail-

able. Let us consider the orchard-feeding problem. It is by no means a simple matter to plan the practice which shall prove best for a given orchard. Suppose it is an apple orchard brought to the age where it should produce 400 to 500 bushels of apples per acre per year. What will be its probable needs for water? Four hundred or 500 bushels of apples would contain 4,440 to 5,550 pounds of dry substance, and there would probably be produced at least an equal weight of leaf and twig, making in all 4.44 to 5.55 tons of dry product, which would require not less than 18 to 22 inches of rainfall to mature it, at the rate of 450 pounds of water per pound of dry substance, or at the rate of four inches of rainfall per ton.

We receive at Madison, Wisconsin, between May 1 and October 1, an average of nearly 18 inches, so that during about one-half the years there may be sufficient rain to produce 400 bushels of apples per acre, provided there is no loss of water by drainage, no unnecessary loss by surface evaporation

from the soil, and provided the soil carries an abundance of other plant food easily within reach of the roots of the trees.

What are the comparative merits and efficiency on the physical condition of the soil, on the maintenance of plant food, and on available soil moisture of (1) clean cultivation alone, (2) clean cultivation and mineral fertilizers, (3) clean cultivation with animal manure, (4) cultivation and cover crops plowed under, (5) sod with grass cut and left where it grew, and (6) sod with grass cut and used as a mulch around the trees?

In our field studies in four states we found, for each of eight soil types, that the amount of moisture at the end of the growing season, under clean tillage, was less than the equivalent of one-half inch of rainfall greater than it was under a crop of corn growing on one side, and under a crop of potatoes on the other. The soil had received the same cultivation in the three conditions, a 3-inch mulch being developed after every rain until the corn and potatoes were

laid by, and often enough to keep the land clean, continuing the cultivation on the fallow ground until near the end of August. We also found that the evaporation of moisture from uncultivated, continuously moist soil was but 1.7 inches less, during 100 days, than it was from the same area of soil bearing a crop of corn which yielded at the average rate of 13,881 pounds of dry substance per acre.

These results may seem to contradict the general teaching regarding the efficiency of earth mulches and the value of cultivation to conserve soil moisture. They do not, however, and they have a very important bearing upon the practices of orchard management which have been specified. So soon as soil becomes very dry it is extremely effective as a mulch, but so long as it remains moist it conducts water rapidly and the evaporation from it may be much faster than from a free water surface. The year of the experiments cited was one of even distribution of rainfall in the four states, which amounted to between 18 and 22 inches for

the growing season, so that, although the fields were repeatedly cultivated to restore the mulch, and after each rain, the mulch effect was destroyed often enough to permit the total loss of water by evaporation to be nearly as great as it was where the crops were growing. The crops dried the surface soil so much more than the fallow ground did, that under the crops the mulch was more quickly restored and more effective than that on the fallow ground.

From these facts it follows that growing of a crop in an orchard does not deplete the soil of its moisture so much more than the losses from naked cultivation would, during those years when the rainfall is good and well distributed, as might at first be expected. But in regions of small rainfall, and during seasons of drouth in humid climates, and especially when the intervals between rains are long, the growing of a crop in the orchard must have a very pronounced effect upon the moisture left available to the trees, because the crop must take not less than two to four inches of rain for each ton of dry

produce per acre. The average amount of water carried in the surface four feet of the soils we have cited was only about 13 inches, and less than half of this can be used by the crop and still leave the moisture content sufficient for rapid growth.

If, however, the orchard is in sod and the grass is cut three or four times during the season and left where it falls, there occurs a week to 10 days between each cutting when the soil is under a very effective mulch and when the evaporation from the crop is relatively small, so that we need not be surprised to find a critical test of the question to show that this type of orchard management may really conserve quite as much or even more moisture, in humid climates, than does naked tillage, and there are other very great advantages associated with this method. Whenever rains come, even though they be heavy, and where the surface may be far from level, the rain is compelled to enter the soil where it falls, causing it to be uniformly wet and no washing or injury to texture can result, as may be the case with

naked tillage. Besides this, the water is likely to enter the soil more deeply, and the cut grass provides an effective mulch the moment the rain ceases, except in so far as the growing crop uses moisture.

But the loss of moisture through the crop cannot be counted entirely a loss to the orchard, for the reason that it is helping the grass collect, from as deep in the soil as its roots grow, soluble plant food, bringing it up where a large part of it will ultimately be returned to the surface soil, placing it where the most active feeding roots of the trees are located. We have found the sap of most plants, in their succulent stage of growth, extremely rich in all of the essential soluble plant food materials, and that this is very readily and quickly washed out. All are familiar with the great injury done to hay by a drenching rain, which washes out its soluble organic products and with them the nitrates, sulphates and carbonates of lime, potash and magnesia, together with phosphates. With the repeated cuttings, therefore, of the cover crop, whatever that may

be, the leaching of the rain must return to the soil a part of the food which the crop has gathered, and this is turned over to the tree roots in the most available form and place. Even the nitrogen, potash and phosphorus which have become fixed for the time being begin at once to be liberated and gradually turned back into the soil, so that the grass cover, repeatedly cut and left where it falls, exercises a continuous pumping process, bringing plant food into the surface 6 inches from depths as great as 4 feet, placing it in pre-eminently the best place to serve as food so long as the soil is sufficiently moist for strong feeding.

The experiments of Professors Green and Ballou of the Ohio Experiment Station along these lines are extremely illuminating, fundamental and important, and particularly so are the results they obtained from the sod-mulch treatment where the grass, when cut, was placed about the trees year after year and permitted to leach and rot there. By this treatment the grass gathered food from all over the orchard and from a

depth of three to four feet, and this was concentrated in the soil near the surface and immediately about the trunks, widening the area as the tops and roots spread. It was found that the fine fibrous roots of the apple trees even developed strongly above the ground, forming a dense mat at the bottom of the mulch itself, where it was crumbling into mold and being transformed into humus, and where the leaching from every rain brought down added food. It was found also that in the surface 6 inches, and below, to a depth of 1 foot, the root development was markedly stronger than it was under the cultivation and cover crop treatment. Undoubtedly the much larger root development under the mulch was the result of the habit of the plant to develop its roots most strongly where there is the best feeding, and it is quite probable that in this case it was plant food substances other than soil moisture which determined the root concentration. Whether this concentration of the mulch about the trees is the best practice may be open to question. It is the general

practice in China and Japan to fertilize chiefly under the tree tops, the Japanese rule being to apply fertilizers to a circle equal to two-thirds that covered by the top. The tea orchards, after the bushes become large, and especially on hillsides, are kept very heavily mulched with straw or litter of some kind, and we saw it a full foot in depth, covering all the ground. In China, too, mulberry orchards are fertilized most strongly directly under the tops. We saw cases where the soil had been entirely removed to a depth of three or four inches over a circle not quite equal to that covered by the top, and this covered with a layer of silkworm droppings together with the bits of leaves not eaten and the molted skins, thus returning to the soil all except the silk which had been removed, and this covered by replacing the soil. Indeed, in their general practice of "plant feeding" these people nearly always apply the food very close to the base of the stems rather than uniformly over the soil surface.

In the case of clean tillage, if this is fol-

lowed year after year, it must impoverish the soil of its organic matter and nitrogen; there would not be a large saving of moisture in humid climates except during long dry spells; bacterial action would be greatly reduced, so that relatively small amounts of phosphorus and potassium carried naturally in the soil could be rendered soluble and available to the trees. The texture of the soil would deteriorate, and unless the surface was level there would be serious washing.

If mineral fertilizers were used to keep up the plant food there would still be a rapid loss of organic matter, and the impairment of the soil texture might be even more rapid and very serious on clayey soils if the nitrogen were supplied in the form of Chili saltpeter, for the reason that the sodium of the nitrate becomes converted into the carbonate when the plant removes the nitric acid, and the carbonate is the "black alkali" of the west, which everywhere has the tendency to dissolve humus and puddle the soil. In this impaired condition a higher per cent

of the soil moisture becomes unavailable to the crop, soil aeration is less perfect, rains penetrate the ground less readily, and there is greater danger of injury by washing.

Where an abundance of organic manure is used, with naked cultivation, and where the orchard is level, much better results will be secured and quite likely a higher available water content could be maintained if sufficient care were exercised in the cultivation.

Where the cover crop is used and this is turned under either late in the fall or early in the spring, and especially if the cover crop is some legume, which under the conditions develops nodules strongly on its roots, nitrogen would be gathered from the air, and organic matter in the soil would, through its decay, liberate the phosphorus and potassium present in the soil, and would render any rock phosphate applied as a fertilizer soluble and available to the orchard. In this treatment it should be remembered that thorough, frequent cultivation, especially in the spring when the soil is moist

and until the new crop of fibrous feeding roots from the trees has developed into the surface soil, does much more than conserve soil moisture. Indeed, one of its main advantages is that of developing plant food through its stimulation of stronger bacterial action. The mulch also performs an important function in preventing the plant food from rising into the surface where the soil becomes dry and where it is beyond the reach of the roots.

Wherever the straw or litter mulch is practicable in market gardening and small fruit growing or in orcharding it has many desirable effects to recommend it as a rational treatment. It is a good method of fertilizing, adding both organic matter and ash ingredients, which gradually leach into the soil with the greatest uniformity of distribution. It conserves moisture most effectively, both by reducing evaporation and inducing even, deep penetration of the rainfall; it avoids soil washing and soil puddling and it helps to control weeds.

Thorough, deep drainage and deep, strong

granular structure of the soil, permitting deep, complete aeration and easy, effective drainage, are indispensable conditions for permitting soil moisture to render its greatest service both in feeding the crop above ground and in feeding the crop of soil bacteria in the ground, which play so important a part in preparing plant food for the crop above ground, whatever that may be. To produce and maintain this structure there must be ample underdrainage and the soil must be kept supplied with an abundance of organic matter and an abundance of lime carbonate, both of which help to maintain strong granular structure, as well as to contribute plant food, first by strongly favoring the solution of the insoluble potassium and phosphorus compounds in the soil, and by direct addition of plant foods themselves.

The late plowing in of stable manure in the fall, leaving the surface rough and loose, and then the earliest thorough and repeated stirring of the soil in the spring, is the best possible treatment to conserve winter rain and snow, to save moisture which comes

early in the spring, and to enrich the soil with immediately available plant food such as will stimulate quick, strong growth and deep rooting, and so condition the crop as to enable it to make the most possible out of the available soil moisture and other plant foods and so give the largest practicable returns.

CHAPTER V

PRINCIPLES AND PRACTICE OF EARTH MULCHES

HOW *much water may earth mulches save?* In a series of trials with different soils exact comparative results were obtained, showing that, in the case of a black marsh soil, the loss of water from the firmed soil surface was at the rate of 4,660 pounds per acre and per day greater than from the same soil under a one-inch mulch; that it was 6,360 pounds greater than from a two-inch mulch; 6,632 greater than from a three-inch mulch and 6,710 pounds greater than from a four-inch mulch, per day and per acre. From a sandy loam the losses per day and per acre from the firmed soil surface were greater than from the one, two, three and four-inch mulches by as much as 7,356, 8,044, 9,080 and 8,522 pounds; while from a virgin clay loam the losses from the firmed

surface exceeded those from the one, two, three and four-inch mulches as much as 23,080, 28,686, 30,496 and 30,602 pounds per acre and per day. Under the conditions of these trials the firmed soil surface lost water by evaporation at the rate of 11,760 pounds from the black marsh soil; 14,830 pounds from the sandy loam and 48,280 pounds from the clay loam per day. These are equal to rainfalls of .052, .065 and .213 inches of water on the level lost daily by surface evaporation from the respective firmed soils.

Saving from frequent cultivation. Critical experiments have shown that when the same soil was left with its surface not cultivated it lost water by evaporation at the rate of 14,482 pounds per acre and per day, but when cultivated one inch deep once in two weeks the loss was 3,458 pounds less; when cultivated once per week and one inch deep the loss was 3,582 pounds less, and when cultivated twice per week the same depth of mulch gave a loss of 3,926 pounds per day and per acre less than from the firm soil.

When the cultivation was two inches deep the cultivation once in two weeks saved 2,298 pounds; the cultivation once per week saved 3,440 pounds; and the cultivation twice per week saved 4,174 pounds of water per day and per acre. And when the cultivation was three inches deep the moisture saved with the cultivation once in two weeks was at the rate of 2,242 pounds; the cultivation once per week saved 3,852 pounds; and the cultivation twice per week saved 4,582 pounds per day and per acre.

WATER SAVED BY EARTH MULCH.

Cultivated	1	2	4	times in 2 weeks
1 inch deep	3,458	3,582	3,926	pounds of water saved
2 inches deep	2,298	3,440	4,147	pounds of water saved
3 inches deep	2,242	3,852	4,582	pounds of water saved

From this table it is clear that the cultivation of greatest frequency has saved the most water and the cultivation of least frequency has saved the least. Look now at column 1, in the table, where the cultivation was once in two weeks. Here the greatest loss was when the cultivation was three inches deep. This brings out clearly one of

the principles underlying frequency of cultivation. Where the deep mulch lies for two weeks in contact with the damp undisturbed soil it gradually becomes moist and compacted by the capillary rise of moisture into it, and this compacting and the wetting increase the rate at which the moisture is drawn up from below, so that when cultivation is repeated at the end of two weeks there is a large volume of wet soil to be brought to the surface, which mechanically increases the loss from the field. But when the cultivation is more frequent the entire mulch is kept drier and the rise of water into it is correspondingly slower, and hence when the soil is stirred there is less moisture to be brought mechanically to the surface and for this reason a smaller loss from the field.

When the surface soil has been thrown into a loose, incoherent layer, the position in which the soil grains have been left is very unstable, so that the slightest cause tends to throw them down and bring them nearer together. The alternate expansion and con-

traction of the soil, due to the great changes in temperature which occur between day and night, cause the loosened soil to gradually fall together and become more compact. The wind blowing over the dry surface breaks off the loose and finer particles, and these fall down and help to make the large spaces smaller. Then, as the pores of the soil become smaller, the water from below is brought nearer to the surface again and, as the surface becomes moist, the large cavities tend still further to close up and so destroy the effectiveness of the mulch. But nothing renders a mulch ineffective so quickly as a drenching rain.

It follows, therefore, that the frequent or constant use of the light harrow on corn and potato ground until they are well above the surface is helpful, not simply in keeping ahead of the weeds, but also in maintaining a thoroughly effective mulch, which is just as important as killing the weeds.

It has been shown that firming the surface by rolling tends to increase the water in the surface soil and to make the loss of water

greater. Now rains not only firm the surface and so increase the loss of water from it, but they often act in another way to draw the water to the surface and so increase the loss. In my earlier studies of soil moisture I frequently found, by taking samples of soil just before and again after rains, in the same places, that the ground at some distance below the surface was actually drier than it was just before the rain. Not only this, but I was able to verify the observations by wetting areas of natural field soils with known quantities of water. In this way I found that the surface foot of soil contained not only the water I had added to it, but also a certain portion of the water which before the wetting lay deeper down in the ground.

Now the facts are, that soils after reaching a certain degree of dryness fail to carry water upward as rapidly as they formerly did; then when a rain falls upon them in this condition they not only hold that which falls, but they actually suck up from below an additional supply. This being true, it can readily be understood how ground al-

lowed to lie unstirred may actually become drier than it would have been in the same time if it had not rained. The practical lesson to draw from these facts is to stir the ground just as quickly after a rain as is possible and not puddle it.

What has been said in regard to rains tending, at times, to dry the lower soil, has an important bearing on the watering of transplanted trees or other plants in times of drouth, for it is evident from what has been said, that if only a small amount of water has been applied to the dry surface its effect will be to draw away from the roots below a portion of the water which is there ready for their use. Evidently then, if watering is resorted to at all in these cases, it should be so plentiful as to completely saturate the surface soil so that the water will percolate downward rather than be drawn upward. This is why, as practice has proven, it is better to water, if at all, not so often, but thoroughly when it is done.

So, too, those who are practicing irrigation for market gardening find it better to

irrigate less frequently, but thoroughly, and then follow as soon as it is safe to do so with thorough and frequent surface cultivation, because in this way less water is required and the surface soil is not so often cooled down below the temperature at which the niter germs and allied forms rapidly develop the fertility from the heavy dressings of manure which have been applied. Neither is the air shut out so long from the surface soil, which is just as important to the development of fertility as the manure itself or the right temperature.

So long as the soil mulch is well loosened and thoroughly separated from the firm ground beneath, and especially after the mulch has become quite dry, little can be gained by stirring the soil. Indeed, it must be ever kept in mind that it costs to cultivate, and when this is done without need the labor is a loss. Further than this, late in the season when the surface of the ground has become relatively dry, positive harm may be done by unnecessary cultivation, because, at this season, many plants put up,

very close to the surface, great numbers of fine roots in order to avail themselves of plant food which is concentrated near the surface by the capillary rise of soil moisture, and to utilize the moisture which may condense upon the soil grains in the form of dew within the surface layer of soil, on the coolest nights. To destroy such roots may cause a greater loss by root pruning, cutting the plant off from available plant food which has been concentrated near the surface and from moisture that comes in the form of small showers, than can be gained by saving moisture through a little more perfect mulch.

Frequent cultivation both develops available plant food and retains it in the soil where it can best be used. Frequent cultivation is most important early in the season, because the soil is then wettest and evaporation of moisture is most rapid then, because mulches then lose their effectiveness rapidly, because stirring the moist soil hastens fermentation, and this develops available plant food, and because this gives more complete

destruction of weeds. But the maintenance of a good earth mulch is nearly if not quite as important in preventing the rise of the most immediately available plant food to the surface above the reach of the roots as it is in preventing the rise and loss of the moisture which brings up the plant food with it. We must remember that the most important function of water in plant feeding is to carry essentials to and from place to place in the plant, and so it is important to retain the water with its plant food down where the roots of the crop are, and this is one of the most important things a mulch does. Saving moisture is less than half the good frequent cultivation does. Work the soil deepest early, and shallower later, because the plant food concentrates under the mulch and the roots come to it.

It is fairly well appreciated that good and frequent cultivation, which develops and maintains an effective earth mulch two to three inches deep over fields of corn and other intertilled crops, exerts a profound and very beneficial effect in conserving soil

moisture, but it is not so well understood that the same treatment may also prove equally serviceable in preventing the immediately available plant food materials which the soil moisture carries in solution from being carried to the surface above and entirely beyond the reach of the roots of the crop which may be at the time growing upon the field.

Soil moisture, as it rises by capillarity to the surface, as oil does in the wick of a lamp, carries with it a large per cent of the dissolved lime, potash and nitric acid which chance to be present in the soil through which it is passing; and if these pass the roots without being removed by them and reach the surface, the soil is as effectually robbed of its essential plant food materials, for the time being, as if these had been carried downward, by percolation or leaching, below the root zone. In the first case they may be carried back again by some subsequent heavy rain, or, in the second, be raised again by capillarity if a sufficiently long dry time intervenes; but until such return is

made, the soil, for the crops on the ground, is impoverished to the extent of whatever displacement out of reach takes place.

How great the capillary movement may be in robbing the root zone of its available plant food, depositing it close to the sur-

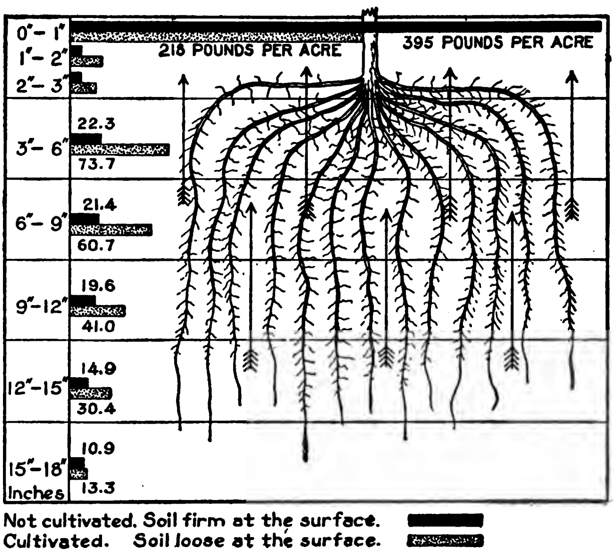


Fig. 11—Effect of capillary movement of soil moisture on the position of plant food materials in the root zone. The black bands and the figures printed with them represent the position and amounts of nitric acid found at different depths in the soil after seventy days of continuous capillary movement where the soil surface was firm. The dotted bands represent the same conditions where the surface was under a three-inch loose earth mulch. Observe that with both conditions of surface a large amount of plant food had been carried above the roots.

face, is shown in the following table and illustrated graphically in Fig. 11. These results are averages of determinations made on six different soil types in North Carolina while investigating the problems of soil management there. It will be seen, from the table, that during the 70 days when these soils were under observation, nitric acid, the form in which crops take most of their available nitrogen, had accumulated in the surface inch to the extent of 395 pounds per acre where the surface of the soil had been maintained in the firm, uncultivated condition; while in the surface of the mulched or loose soil the amount of nitric acid carried into the upper inch was 177 pounds per acre less. With this accumulation of immediately available plant food nitrogen there were also large amounts of potash, lime and other materials, and all of it entirely above the reach of the roots of crops. Glancing down the two columns of the table, it will be seen that even at the depth of 15 to 18 inches the immediately available plant food

is very appreciably greater where the three-inch mulch has been maintained.

DISTRIBUTION OF NITRIC ACID (NO_3) IN SOILS AFTER 70 DAYS OF CAPILLARY MOVEMENT. AVERAGE FOR SIX SOIL TYPES.

Depth, inches	Surface soil firm, pounds per acre	Surface 3 inches loose, pounds per acre
0-1	395.0	218.0
1-2	8.1	26.2
2-3	7.3	21.5
0-3	410.4	265.7
3-6	22.3	73.7
6-9	21.4	60.7
9-12	19.6	41.0
12-15	14.9	30.4
15-18	10.9	13.3
Total,	499.5	484.8

The total amount of nitric nitrogen under the two conditions of surface treatment is very nearly the same, and hence the difference is almost wholly one of distribution, due to the movement of the nitrates by the water as it rose at different rates, by capillarity, through the soil, carrying the plant food materials with it. The nitrates in these soils which are within the reach of the roots are those found between the depths of two to

18 inches, and these foot up 144 pounds per acre more under the three-inch mulch.

The distribution of sulphates also shows the same general effect of capillary action to cause them to collect at the immediate surface above the reach of the roots, the surface inch of the soil under the three-inch mulch having collected 102 pounds of sulphates per acre, expressed as SO_4, while in the firm surface soil there had been gathered 290 pounds per acre, or nearly three times as much. In the soil to which the roots of the crop would have access the earth mulch had the effect of leaving more than double the amount of sulphates soluble in water within the reach of the roots which the firm surface did, or 130 pounds per acre more.

Even in the case of the difficultly soluble phosphate salts, which are absorbed and retained so completely by soils, the firm surface came to contain nearly double the amount which would dissolve readily in water that the loose surface did.

Cultivation, therefore, which develops and maintains a thorough earth mulch over

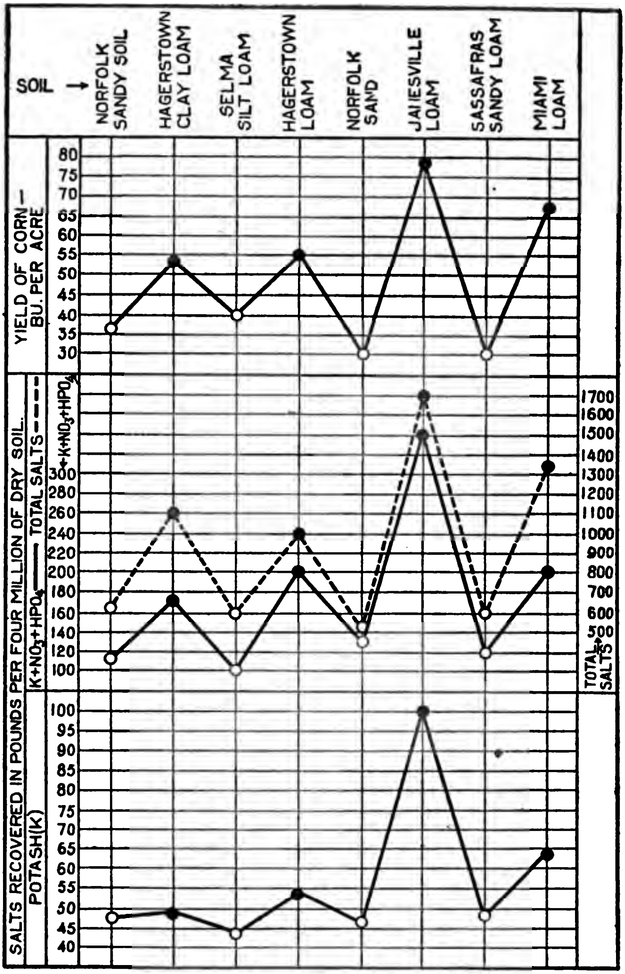


Fig. 12—Shows in the upper curve the yields of corn per acre on eight soil types, two in each of four states. The two middle curves and the bottom curve show how the water soluble potash and other plant food materials increase and decrease with the yields.

the field not only kills weeds and effects a great saving of soil moisture, but in addition thereto it holds the immediately available plant food materials below the surface, where they remain in contact with the roots, and hence where they are serviceable to the crop. We cannot too fully appreciate that the productive capacity of a field for the immediate crop depends not so much upon the amount of plant food material there is in the soil as it does upon the amount that is in the form which soil moisture can take up and hold in contact with the active roots of the growing crop. Whatever, therefore, tends to strengthen this solution about the roots tends to increase the yield.

This relation of yield to the amount of water-soluble plant food material carried by the soil is clearly brought out in Fig. 12, where the yields of corn are seen to increase or decrease as the readily soluble potash and phosphoric acid rise and fall in the different soils. Here it will be seen that there are eight soil types, distributed in four states, in which there is no exception to the large and

small yields going with the large and small amounts of the water-soluble plant food which the soils were found to contain at the time and in the place where the crops were

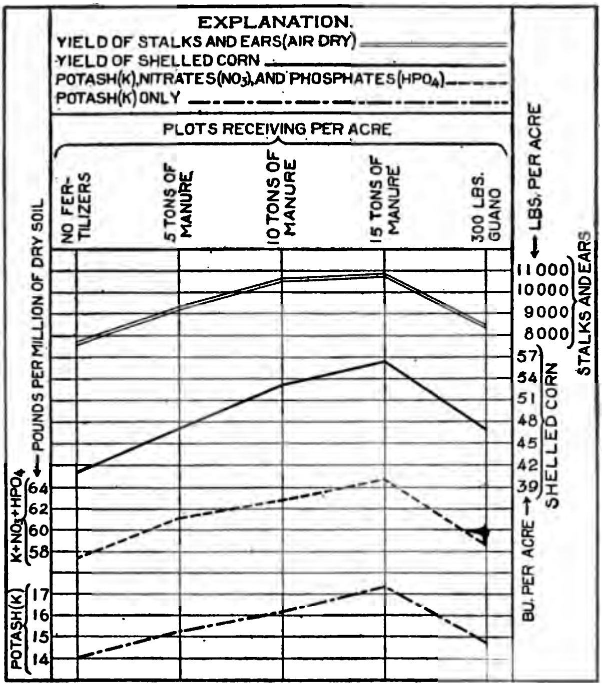


Fig. 13—Shows how the plant food material soluble in water was increased by the addition of five, ten and fifteen tons of manure per acre and 300 pounds of guano, and how the yields per acre increased in relation to the increase in the amounts of water soluble plant food materials.

growing in the field and under perfectly normal field conditions.

To make the evidence still more clear in this matter, the amounts of readily water-soluble plant food material were increased on each of the eight soil types by applying different amounts of stable manure and of guano per acre. When the amounts of the water-soluble plant food in these different soils under the different treatments were determined at different times during the growing season, and the yields also ascertained, it was found that they stood as represented in Fig. 13. From this chart it will be seen that, where the soluble plant food materials were increased, there the yields were also increased. Since crops are sensitive to the amounts of soluble plant food materials carried in the soil; since these plant food materials move through the soil with the soil moisture; and since the movements of the soil moisture are affected in a profound way by methods of cultivation and soil treatment, it can be readily understood that good, thorough and timely cultivation not only kills

weeds, aerates the soil and conserves in a marked manner the soil moisture, but also that it operates in important ways to retain the soluble plant food materials within the zone of greatest root activity.

In the case of the six soils in which the capillary movement of the plant food materials was observed, the mean evaporation from the unmulched or firm surface was 4.027 inches in 28 days; while the loss of water where the soil was covered with a three-inch earth mulch was but .783 inch, or less than one-fifth as great. It is this large difference in the rate of movement of the soil moisture that has effected the difference in the distribution of the plant food materials in the soil.

When the methods of cultivation are such as to intensify the concentration of water-soluble salts at the immediate surface, and where the texture of the soil, the character of the rainfall and the topography are such as to cause frequent surface drainage, there must be, of necessity, heavy losses of soil fertility as the result of such conditions.

Where the granular structure of the soil is feeble, heavy rains, and even very moderate ones, so puddle the immediate surface that the water does not enter the soil readily, but quickly flows to the lowest places, carrying with it the soluble salts which have been concentrated at the surface, and if the fields are furrowed, much of the rainfall is liable to pass away in surface drainage, and with it whatever of salts have been dissolved.

It sometimes happens, when cold, wet, backward springs occur, that the nitrates have been washed from the surface soil into the second and third feet where young plants cannot use them at once. In such cases it may often be desirable to encourage some loss of water by evaporation in order to bring back the nitrates where they will become available to the young plants. It is sometimes a serious mistake, even if the season is getting late, to hurry the planting at a time when the immediately available food has been washed too deeply below the surface, for seeds which germinate quickly and have but a small store of nourishment in

themselves may starve or become weakened before the nitrates have had time to develop or be brought back to the surface.

At such times it may be desirable to harrow deeply in order to dry the soil quickly, and then roll to make the dry soil take up more moisture, and then harrow again, in this way forcing the water and plant food back to the surface where it is needed most. Keep always in mind that if more water falls on a field than is needed it is better to have this removed by evaporation at the surface than to pass away by percolation, for then the plant food dissolved in the water is retained and brought where it can be used to the greatest advantage, while if the water drains away the nitrates are lost.

CHAPTER VI

WHY ARE LIME SOILS STRONG?

IT has long been an adage that "a lime country is a rich country," but the full *why this is so* is yet a matter of many doubts. Pure science has much to reveal before conjectures can be wholly removed and before the how and why of lime in soil productivity can be one of the generally recognized beacon lights in practical agriculture which it is destined to become. And after pure science has done its work, applied science must needs construct the sailing chart for the guidance of the farmer before be can be fully able to develop, conserve and utilize lime with the economy and high efficiency needful for continued crop production. Many of the facts and some of the underlying principles needful for the direction of practice are known and may be stated.

The source of lime in soils. All lime in soils is derived primarily from the primitive

rocks by their reduction to fine fragments, or by their solution, chemical and physical; and, on the average, 3.5 pounds in every 100 pounds of primitive rock is calcium, one of the elements, as are iron, gold, carbon, sulphur, oxygen and nitrogen; and this calcium, united with oxygen, is the lime of commerce, obtained by burning limestone in kilns. But when such rocks are broken down into soil and this is acted upon, as such, by Nature's agencies, the lime dissolves out and is borne away in the drainage waters in immense volumes so large that, on the average, each cubic foot of river water carries to the sea more than 2.1 ounces of lime compounds, eight-ninths of which is lime carbonate, the basis of limestone, the chief ingredient which deposits on the inside of tea kettles, and the lime compound which plays so important a part in determining the productive capacity of soils.

How limestone and lime soils are formed. Much of the more than 300,000 tons of lime carbonate leached out of soils and the underlying rocks and carried into the sea per each

cubic mile of water is again laid down in the shallower waters off shore by coral and shell-forming animals, giving rise to broad stretches and thick beds of limestone material, having entangled with it silts, sands and organic matter in greater or less quantity. These limestone deposits when, by future upward movement of the earth's crust, they come to be portions of the dry land, are again subjected to the processes of weathering, which carry back to the sea the bulk of the lime carbonate, leaving a stratum of overlying soil rich in lime and usually other essential soil ingredients. By the continent-wide glacier-grinding an immense amount of rock pulverizing and distribution took place in comparatively recent times. In this way limestone sections were overswept, and much of the lime rock was broken, ground and spread broadcast, deeply and intimately commingling the lime fragments with soil materials, thus producing soils rich in lime carbonate where otherwise such could not have been formed. This gigantic liming operation of Nature occurred too recently

for the application to have been dissolved away, and we thus have wide areas of soils rich in lime not directly underlaid by limestone. Indeed, most of the northern United States, reaching from the Atlantic to the Rocky Mountains, and lying to the north of the Ohio River, are covered with soils richer in lime on account of this glacial action. In the arid and semi-arid regions of the world, where there is comparatively little leaching, nearly all soils may be rich in lime carbonate because, as the soil and rock decay under the conditions of scanty rainfall, the lime carbonate produced tends to accumulate toward the surface under the influence of capillary rise and surface evaporation of the soil moisture, and so the soils of the western United States are nearly all rich in lime. On the Atlantic and Gulf coasts, where glaciers have not operated, but where heavy rainfall and consequent leaching have prevailed for long periods, the soil content of lime carbonate is necessarily low, and for this reason such soils are naturally less productive than they could otherwise be.

Effect of lime carbonate. In outlining some of the ways in which lime carbonate tends to produce and to maintain rich soils, it should be understood that when ordinary lime is applied to a field, whether it be ground or slaked, it is very soon converted into the lime carbonate by the union with it of carbonic acid from the soil or air, and the beneficial effects it is observed to exert are very largely those due to the lime carbonate thus formed. The only reason for applying burned or slaked lime to soils has been that until recently the burning of limestone and slaking it has been the cheapest method of getting the rock in a sufficiently fine powder so that a small amount may be spread over a large area, and so that a small quantity, by weight, of the lime carbonate has a sufficiently large surface upon which soil moisture may act and dissolve it rapidly, for it is only after it is in solution that its effects in the soil are felt.

One of the most important effects of an abundance of lime carbonate in soils is the influence it exerts in tending to bring about

a bunching of the finest silt and colloidal particles of the soil into larger compound aggregates, thus making what might otherwise be a stiff, impenetrable, impervious and untillable clay, a deep, mellow, open, well-drained, well-aerated soil, rich in available moisture and available plant food, and in which the roots of plants will spread wide and deep, thus enabling a crop to be abundantly nourished when the absolute content of soil moisture and the available plant food may be relatively low. A smaller absolute content of moisture and of plant food material will suffice for abundant crop feeding in a coarse, sandy soil than is possible in a fine clay one, and simply because it has so much less surface upon which soil moisture and plant food can be locked up.

A fine clay soil, weighing 70 pounds per cubic foot, and containing 11 per cent, or 7.7 pounds of water, may be so dry that crops will wilt in it and stop growing, while in a coarse, sandy soil weighing 100 pounds per cubic foot there may be a good supply of moisture when it contains but two per

cent, or two pounds per cubic foot. The reason for this is that a certain thickness of water film covering soil grains is wholly unavailable to plants, and the soil grain surface of the fine clay soil cited is so much larger than that of the sand that 7.7 pounds of water to the cubic foot of soil leaves the thickness of the layer on the soil grain surface much thinner than is that on the coarse sand grains with only two pounds of water to the cubic foot; hence growth is arrested in the one case with nearly four times the amount of water about the roots that permits a maximum growth in the other.

Fine-Grained Soil and Lime. But when a fine clay soil has become thoroughly granulated through the conditions made possible by an abundance of lime carbonate, we have the clay soil converted into one having in effect the coarse-grained texture of the sandy soil, and on the outer surface of these coarser grains water may be stored which is just as available as a like amount and thickness of film carried by the correspondingly large solid sand grains of

the other soil. When the clay soil is maintained in this thorough granular condition it has an immense advantage over a coarse single-grained soil of identical chemical composition. This is so because, about the immense surface within the compound grain of the fine soil, soil moisture, with its contained chemicals, is not only elaborating soluble plant food far faster than is possible on the small surface of the coarse, single-grained soil, but at the same time, when the film of moisture surrounding the fine absorbing root hairs becomes continuous with that surrounding the compound grain, the store of soluble plant food generated and gathered within the compound grains is able to spread outward by diffusion into the water film about the root hair as that water and its content are drawn into the plant.

Then, too, this granular compound structure of fine clay soils, when it extends deeply and good underdrainage exists, permits the excess of rainwater to be drained off with far less leaching effect than is necessarily asso-

ciated with corresponding rainfall conditions with the coarse, single-grained soils. When rain falls upon a field thus deeply granulated the water, as it moves downward by gravity and by capillarity, is at first drawn into the crumb structure until the compound grains have become saturated. At the same time this is taking place the readily soluble salts which had gathered in the surface soil by capillary action and evaporation since the preceding rain enter the compound grains with the water taking them up, and, if the granulation extends to a good depth and the open space in the soil is large, nearly the whole of a heavy rain may be thus stored within the compound grain structure, together with the soluble plant food it has taken up.

In the case of coarse, single-grained soil, however, the rain percolating downward tends to sweep from the surface of the solid soil grains their original water films more strongly charged with the dissolved plant food, leaving behind only the thin unavailable layer of water which becomes over-

spread with the dilute freshly fallen rain. There must in such cases be more leaching under like rainfall conditions, both because there is less volume capacity for storing water, and for the reasons stated above.

Again, when a fine-grained soil is not well granulated, and is without large open passageways to the underdrainage, the excess of water which must drain away moves through the soil much more slowly, thus giving opportunity for the soluble plant food held within the unavailable stationary films of water to diffuse outward into the stream of excess water and hence to be carried away, as it could not be with the more open structure that is associated with ample, strong granulation coincident with an abundance of lime carbonate in the soil. This is what does actually happen to so many of our southern soils, where the granulation is feeble as well as incomplete, permitting the soil to wash badly with every heavy rain, the streams running turbid, bearing away solid and liquid plant food.

It is not intended to convey the idea that lime carbonate is the only essential factor in developing and maintaining the best physical condition of soils. It is, however, one of the essential factors, especially in the heavy clay types; and all limestone soils which result from the decay of lime rock in place are, with few exceptions, of the clay type.

Development of available plant food. From the standpoint of the chemical and life processes in the soil which are concerned in the elaboration of plant food, lime carbonate plays an extremely important role, and the part it takes in producing from humus the nitrogen food of crops takes first rank. In the decomposition of humus by bacteria in the soil nitric acid is formed, just as vinegar is the final product in the fermentation of sugar by yeast and the mother of vinegar. The presence of any considerable amount of free nitric or other acid in the soil moisture checks and finally arrests completely the further formation of nitric acid from the humus. But when there is

present an abundance of lime carbonate, associated at the same time with other conditions favorable for nitrification, the lime of the carbonate is appropriated by the nitric acid formed, setting free the carbonic acid and leaving, in place of the lime carbonate, lime nitrate, which is the chief compound from which agricultural crops derive their supply of nitrogen. In this neutralization of the nitric acid by the lime the soil is prevented from becoming sour, and nitrification goes forward continuously and at a rapid rate. At the same time that the nitric acid is passing from the organism which excretes it as a waste product to the lime of the carbonate to become neutralized, this free nitric acid and the carbonic acid too, in its turn, when it is set free from the lime by the nitric acid, act together in increasing the dissolving power of the soil moisture for the other essential plant food elements in the soil. Thus it is seen that the carbonate of lime not only takes a necessary part in putting the nitrogen of humus in food form to supply crops, but it also aids

in bringing other plant food elements into available form as well; and it is a common experience that soils comparatively poor in potash and phosphoric acid, if only the humus and lime content are kept high, may yet produce large yields, because the same action which develops from the humus the lime nitrate, sets free in the soil moisture more potash and more phosphoric acid. Lime sulphate, or land plaster, exerts a similar effect in favoring nitrification, but is never naturally so abundant in soils. Other bases, if free to unite with the nitric acid, may favor nitrification, but none of the naturally available bases is as serviceable as lime.

We have thus stated two of the main reasons, one physical and the other biochemical, why "a lime country is a rich country"; why an abundance of lime carbonate in a soil is generally associated with one highly productive. To set out all of the ways in which lime carbonate aids in maintaining soil productivity would require the discussion of at least a dozen other lines of activity or influence.

CHAPTER VII

PHYSICAL FEATURES OF SOILS WHICH INFLUENCE THEIR ABILITY TO FEED CROPS

SOILS are mechanical mixtures of air, water, organic matter and a great variety of minerals. Through the play of physical, chemical and vital forces this mixture is in constant interaction. The product of this interaction is a very complex solution, which is the soil moisture.

Plants place their roots so as to withdraw this solution from the soil and, except the carbon derived from the air through the leaves, this solution constitutes their entire food. If this solution is continuously maintained in the soil; if it is sufficiently abundant; if it has the right concentration and composition, then, with the right temperature and abundant sunshine, only accident or disease can prevent large yields.

DEPTH OF SOIL

When all other conditions are similar, the best soils are those which are congenial to the roots of crops throughout a depth of four feet. There is a wide difference in the depth of root penetration into the soil, but these differences are determined, in our opinion, more by soil conditions than by the habit of the plant. There are few crops which will not draw upon more than four feet in depth of soil if the soil is in good condition. It is important to know and to control the conditions throughout a depth of at least four feet of soil.

PROPORTIONAL PARTS

When the surface foot of soil is in prime physical condition, about seven inches out of the 12 are occupied by air and soil moisture, and only five inches by the mineral grains and organic matter.

In southern Wisconsin we have found the ratio between the solids of the surface four

feet of soil, and the space occupied by air and water, to be:

Depth	Solids	Air and Water
1 ft.	5.5 in.	6.5 in.
2 ft.	5.6 in.	6.4 in.
3 ft.	5.8 in.	6.2 in.
4 ft.	6.2 in.	5.8 in.
Total,	23.1 in.	24.9 in.

But in Maryland, where the rainfall is heavier, where the lime content of the soil is much less, and where the ground does not freeze deeply, the ratios were found to be:

Depth	Solids	Air and Water
1 ft.	6.2 in.	5.8 in.
2 ft.	6.7 in.	5.3 in.
3 ft.	7.5 in.	4.5 in.
4 ft.	7.52 in.	4.48 in.
Total,	27.92 in.	20.08 in.

These relations show that the surface four feet of soil has an absolute water capacity of from 20 to 25 inches, or some five to six inches of water to the foot of soil. But not all of this water can be retained in the surface four feet of a properly drained field.

PROPORTION OF WATER RETAINED

A critical study, in the field, of the amounts of water retained by eight soil types, two in each of four states, during the growing season from May to September, showed that the mean amount of water retained in the surface four feet was about 14 inches, when the absolute water capacity was 21.7 inches. The rainfall during this season was remarkably well distributed and amounted to 18.87, 18.75, 19.78 and 19.44 inches, respectively, in the four states, measured on the fields where the observations were made. Under these conditions the soils carried continuously throughout the growing season an average of 14 inches of water, the minimum amount found being 10 inches in the best drained sandy loam, and the largest amount was 17 inches in the heaviest clay loam.

NOT ALL SOIL MOISTURE IS AVAILABLE TO CROPS

It is important to remember that not

nearly all water retained in a soil is available to the crop growing upon it, and in these eight soils nearly one-half of that retained by capillarity could not be recovered by the crop with sufficient rapidity to permit maximum yields.

AMOUNT OF AIR IN SOILS

In the eight soil types studied in the field an average of nearly 23 inches of the surface four feet was occupied by the organic matter and mineral soil grains; a little more than 14 inches was occupied by water, and a trifle more than 11 inches by air. The soil minerals and the soil moisture usually increase with depth, while the soil air and the organic matter decrease downward. It is chiefly because the soil air decreases downwärd, and because it is renovated so slowly by soil ventilation that the subsoils in humid climates are able to contribute less to plant growth than are those in arid regions. If the surface four feet of every soil could be as thoroughly ventilated as the surface foot,

much larger yields would be possible, and a less number of inches of water, applied in irrigation or falling as rain, would be necessary for large yields.

THE PLANT FOOD CONTENT OF THE ROOT ZONE

The dry soil of the surface four feet will, on the average, weigh rather more than 350 pounds. Hopkins gives the analyses of a wheat soil in Scotland, an alluvium soil in Holland, four loess soils in the Mississippi valley, an adobe soil in New Mexico, a corralline limestone soil from Bermuda and 10 residuary soils from as many different rock formations in Maryland. An average of all of these, when given equal weight in making up the average, indicates that 350 pounds of soil, the mean weight of the surface four feet, may contain

Phosphorus	Potassium	Magnesium	Calcium	Sulphur
.36 lb.	5.35 lbs.	3.14 lbs.	6.33 lbs.	.29 lb.

These quantities, multiplied into the number of square feet in an acre, would show

Phosphorus	Potassium	Magnesium	Calcium	Sulphur
7.85 tons	116.61 tons	68.32 tons	137.15 tons	6.26 tons

This is an inventory of the farmer's stock of plant food elements, stored in the root zone of his fields. But it must be observed that, as in the case of the soil moisture, a very large proportion of these food elements must forever remain unavailable to crops where large yields per acre are expected.

It is important to realize that such large amounts of plant food elements are stored in the surface four feet of all good soils. It must become the business of the farmer and fruit grower, sooner or later, to learn to apply the means whereby, through proper soil management, these several stores shall be extracted from the solid minerals of the soil and transferred to the soil moisture with sufficient rapidity to meet the needs of crops when producing large yields.

The Chinese, Korean and Japanese farmers centuries ago came to realize the immense stores of plant food elements locked up in the surface four feet of their small holdings, and it has been their application of methods of soil management, aiming to bring these plant food elements

into solution as the crop needs them, that still enables them, after forty centuries of cultivation, to continue feeding their dense populations of today.

They work enormous quantities of soil and subsoil into compost with organic matter, thus effecting the solution of potash, phosphoric acid, lime and magnesia carried in the soil particles. They stack up green legumes, saturated with mud, and allow them to ferment together. They carry soil from their fields and throw it into reservoirs or into the canals and allow it to ripen there and then carry it back. They use immense volumes of soil and subsoil, making it into huge brick for use in their chimneys, kangs and houses, mixing it with chaff and cut straw. These are all returned to the fields as fertilizer after a period of use. In these ways immense volumes of fertilizers are manufactured directly from their soils and subsoils, canals increasing in size and length and the village reservoir growing larger and deeper with years of use.

AMOUNT OF SOLUBLE PLANT FOOD IN SOILS

The concentration and the composition of soil moisture, so far as these are influenced by the presence of plant food, primarily determine the feeding power of a soil. Productive soils are always charged with rich soil moisture. On the other hand, no matter how perfect all other conditions of a soil may be, if the soil moisture is deficient in one or more essential plant food elements, growth must be retarded.

An abundance of water and plenty of root room make the most of a small food supply in the soil, but it is most emphatically true that the highest duty of water is made possible only where there is an abundance of plant food of all kinds. In a country of deficient rainfall and where irrigation must be practiced the maintenance of a high plant food content in the soil, and the maintenance of prime physical conditions, are of the greatest importance.

From the surface four feet of four strong soils, producing at the time large yields, we

were able to recover, with distilled water, in a three-minute washing, thus diluting the soil moisture, as many pounds per acre as:

Potassium	Calcium	Magnesium	Nitrogen	Phosphorus	Sulphur
		Four good soils			
264	1016	348	82	84	598
		Four poor soils			
182	395	177	30	48	258

Under these differences in the concentration of the soil moisture in the two groups of soils the yield of corn and potatoes was 2.5 times greater where the soil solution was most concentrated.

An examination of the plant sap for these six essential plant food elements showed that the same number of plants, growing on the same areas of soil carrying the strong solution as upon those carrying the weaker solution, had recovered from the soil 2.64 times as much potash; five times as much lime; six times as much magnesia; seven times as much nitrogen; 2.5 times as much phosphorus; and four times as much sulphur,

judged simply by the amounts of these substances which could be washed out of the tissues with distilled water.

RELATION OF PLANT FOOD, IN SOLUTION, TO SOIL PARTICLES

When a clean glass marble is laid in water and then removed it comes forth with a layer of moisture held by the mutual attraction of the water and glass. Every particle of moist soil is similarly invested with a layer of water, even when the soil is reduced to the air-dry condition. If a clean glass marble is dipped into a solution of potassium nitrate, it comes forth with a mixed layer of water and nitrate and, what is remarkable, and very important from the agricultural standpoint, the concentration of the nitrate in the layer of water nearest the marble becomes stronger than it was in the original solution.

In the case of the soil moisture solution the same conditions prevail, the concentration being greatest nearest the surface of the

ultimate soil grain and within the complex soil granules or crumbs.

THE CONCENTRATED FILMS NOT READILY REMOVED

When three small glass marbles which had been dipped into a dilute solution of potassium nitrate were three times washed in 100 c. c. of distilled water, it was found that the film of water adhering after the third washing was still more concentrated than the original solution. We have also found that a carefully cleaned coarse quartz sand, after having been placed in a dilute solution of potassium nitrate and later carefully washed 10 successive times by stirring in fresh lots of distilled water, still retained, in the surface films of water adhering after the solution was drained away, a sufficient amount of nitric acid to represent 41 pounds per acre in the surface foot.

In such cases the layer of water, with its salts in solution, is held so rigidly to the solid surface of each grain that, even when

they are vigorously stirred in pure water, the original layer of water with its nitrates moves about in the water with the individual grain and so is not diluted, its strength decreasing only by the slow diffusion of the substances in solution outward into the pure water.

It is this rigid adherence of water films to soil grains, and the concentration of plant food substances in them, that permit soils to store such large amounts of plant food in water-soluble form. We have found that by repeatedly washing the same soil sample eleven times in quick succession it was possible to recover three times the amount of plant food elements that were secured by the first washing. It was also found that by washing the same sample of soil 11 times, drying it each time after washing, more than six times the amount of plant food elements recovered by the first washing were removed.

THREEFOLD ROLE OF SOIL PARTICLES

It is thus seen that the solid portions of a

soil play a very important role in its function of feeding crops.

1. The soil grains provide an enormous surface over which the nutritive soil solution is spread and retained and against which the root hairs of plants lay themselves for its absorption.

2. Over these enormous surfaces chemical and physical changes go forward, which help to restore the strength of the soil moisture solution as this is depleted by plant feeding or by leaching.

3. They provide the proper home for the activities of all those forms of microscopic soil life which play the great part in breaking down organic matter, initiating and facilitating so many of the physical and chemical changes which give rise to the soluble plant food substances found in the soil moisture.

EFFECTIVE DIAMETER OF SOIL GRAINS

One of the most fundamental physical characters of a soil is the effective diameter of its grains or units. In the very coarse,

sandy soils the effective diameter is the mean of that of the sand particles, but in the case of loamy and clay soils the effective diameter is the mean size of the clusters of soil particles which give to them their degree of freedom of movement of air and water.

So many of the important qualities of a soil are dependent upon the effective diameters of its grains, and the effective diameter of most soils is so profoundly affected by good and bad methods of soil management that it is extremely important for the practical man to have the clearest possible ideas regarding this characteristic and how it influences the behavior of the soil in the field.

EFFECTIVE DIAMETER DETERMINES RATE OF FLOW OF AIR AND WATER

Take two cubic feet of soil, one with effective grains so coarse that 100 of them span a linear inch, and those of the other so fine that 12,400 cover the same length. Under a pressure of 10 centimeters of water, not quite four inches, a cubic foot of air will

flow through the first in about one minute, while it will require 20 days, lacking less than an hour, to flow through the other.

There is an equally great difference in the flow of water through such soils, where the passageways are dependent wholly upon the effective size of the soil grains.

An effective diameter of 100 grains to the inch gives a pretty coarse, sandy soil, but it is a very excellent degree of granulation for the heavy clay types. No soil in agricultural condition can have so small an effective diameter as 12,000 to the inch, although many soils have particles even smaller than this. A soil with effective diameters in such a condition would represent about the worst puddled black alkali adobe, practically impervious to both air and water.

Lay down spheres in rows such that 100 each way just cover a square inch. There are formed 10,000 triangular pores, each about one-third the diameter of the spheres. Through these air would flow at the rate named for the coarse, sandy soil. Lay down on another square inch other spheres such

that 12,000 each way shall just cover the surface. Here 144,000,000 triangular pores are formed, where 10,000 were before, and we have the structure of the worst alkali adobe soil, through which both air and water can move only with the greatest difficulty. The finest clay soils, when in passable working condition, may have their ultimate particles bunched into effective grains such that 4,000 of them will span a linear inch, and then 783 minutes would be the time required for the flow of a cubic foot of air through a cubic foot of the soil, instead of one minute, as would be the case when in the very best textural condition.

EFFECTIVE DIAMETER DETERMINES THE INTERNAL SOIL SURFACE

Drop into a box, one foot on each edge, a granite sphere of the same diameter. The box has a surface of six square feet, the granite ball a surface of 3.1416 square feet. Place eight six-inch boxes inside the one-foot box. The eight will have double the

surface of the one-foot box. Eight half-foot granite spheres, too, will just slip inside the one cubic foot and their surfaces will aggregate just double that of the one-foot sphere. If we pass now to the size where 100 little spheres may be laid along an inch, then 1,200 will span a one-foot box, and the number which will lay up a cubic foot must have a surface 1,200 times that of the one-foot sphere, or between one-eleventh and one-twelfth of an acre. Take the case where 4,000 spheres span the linear inch, and 48,000 the foot. Then a cubic foot of these must have a surface 48,000 times that of the one-foot sphere, or 48,000 times 3.1416 feet, and more than three acres of soil surface within one cubic foot of soil. If we go to the extreme of the puddled fine clay soil, where there may be more than 12,000 grains to the inch, and 144,000 to the foot, then the soil surface must be increased to 144,000 times 3.1416 feet, and this exceeds 10 acres of soil surface to the cubic foot, and more than 40 acres per square foot of field, in the root zone to a depth of four feet.

Fig. 14—Photo-engraving of corn and potatoes growing on Norfolk sand, Upper Marlboro, Maryland, where different amounts of farmyard manure had been applied to the soil. The six rows near the center of the engraving, where the corn and potatoes are smallest, stand on the untreated portion of the field; the second six rows to the left received five tons of stable manure per acre; the next six rows ten tons and the next fifteen tons per acre; while the first six rows to the right received 300 pounds of guano per acre and the next six rows fifteen tons of stable manure. The five conditions of treatment of the soil were repeated four times across two acres of land, on each of eight soil types in four states. ("Investigations in Soil Management," F. H. King, 1904, p. 15.)

Fig. 15—General view of cornfield on Miami Loam, Janesville, Wis., showing influence of different amounts of manure. The low corn in all cases marks the areas on which nothing was added to the soil, and the places of maximum height are those where the 15 tons of manure per acre had been applied. The camera was stationed some 60 rods distant and yet the rise and fall of the corn on the successive plots is evident. ("Investigations in Soil Management," F. H. King, 1904, p. 15.)

INCREASED SOIL SURFACE MAKES MORE WATER UNAVAILABLE

It is a common observation among practical men that crops often stand drouth better in sandy and mellow, loamy soils than they do in the heavy clays, although the clay soils may carry at the time much larger amounts of water. One of the chief reasons for this difference depends upon the principle that doubling the surface of a soil upon which water may be spread, and from which the roots may draw their supply, doubles the amount of water which becomes unavailable because it is so strongly held on double the amount of surface. It appears that when the thickness of the water film surrounding soil grains has been reduced to the limit of .000019685 of an inch, or to .0005 m. m., the balance of the water is too rigidly held by the soil surface to make it sufficiently available to crops to permit their producing large yields.

But a film of water of the thickness named, while it would be but .45 per cent of the dry weight of the coarse, sandy soil, of

100 grains to the inch, would be 20 per cent of a soil having grains as small as 4,000 to the inch, and as high as 82 per cent in the case of the puddled fine clay; but in this case such a soil would have the consistency of a thin porridge, the amount of water being more than enough to fill all of the space between the grains.

That this water is not readily available to plants may be easily demonstrated by placing slips of plants in the soil when in this condition and others of the same kind in pure water, setting them side by side in the bright sunshine. Under these conditions it will be seen that the slips wilt more quickly and to a greater extent in the clay than in the pure water.

COLLOIDS AND SALTS IN SOLUTION RENDER SOIL MOISTURE UNAVAILABLE*

It is my conviction that the injurious effects of high per cents of soluble salts in

*See "On the Suspension of Solids in Fluids and the Nature of Colloids and Solutions" in Trans. Wis. Academy of Sci., Arts and Letters, Part I, Vol. XVI, 1908, pp. 275-288.

soil moisture, such as alkalies, are due in part to the strong hold they have upon the water, rendering it less available to the plant. These salts, if the solution is strong enough, may even withdraw water from the protoplasm in the cells of plants after the salts have been imbibed, thus causing it to shrink and interfere with its normal functions.

Fig. 16—Showing water made unavailable to plants when substances are dissolved or suspended in it. First jar, at left, contains one part agar-agar to 49 parts water. The second jar contains two parts sugar to five parts water. The third contains only water. The fourth contains one part dextrine to five parts water. The fifth contains one part clay to five parts water.

If sugar, starch and agar-agar are dissolved in water and slips of plants put in these, with others in pure water as checks, it will be found that those not in pure water will wilt much sooner and more intensely, in bright sunshine. If the slips are placed out of the sun, or where evaporation is

small, those in the sugar, starch, agar-agar and clay will keep fresh nearly or quite as long as those in pure water, showing that the wilting had been due to the difficulty in removing water from the substances named. Colloidal clay and other colloidal substances in soils must exert a similar influence on the soil particles themselves in rendering water unavailable. And it must be the enormous surface possessed by peat soils which causes plants to suffer from lack of water when there are enormous quantities present.

INFLUENCE OF HUMUS ON WATER CONTENT OF SOILS

Much is said regarding the influence of humus in increasing the water content of soils. It does this chiefly through the extremely large surface which it adds upon which the water may be held. It is clear, therefore, that, while it is true that the humus increases the water-holding power, it is not true that an increase of humus in-

creases the water available to the crop to a very large extent, certainly not to the extent that it increases the water-holding power. It may even reduce the available water and cause crops to suffer in times of drouth more seriously than would be the case with a smaller content of humus and organic matter. The great advantage of humus and organic matter in the soil grows out of the chemical changes and soluble effects which are associated with the decomposition of humus and organic matter by the microscopic life which feeds upon it.

In the drier parts of China farmers have learned even to pull their crops by the roots and compost everything coarse, until the organic matter is largely destroyed and its surface very greatly reduced, before they apply it to the soil. In this way they not only make the plant food more quickly available, but they put the organic matter in a condition which prevents it from interfering seriously with capillary movement, and from rendering the moisture in the soil unavailable to the crop.

TOO LARGE A SOIL SURFACE MAY RENDER PLANT FOOD UNAVAILABLE

Since the soluble plant food substances are carried in the soil moisture, and since these are more concentrated in the layers of moisture nearest the soil grains, it is clear that the soils with very large surfaces must not only be able to carry more soluble plant food, but cause a lower per cent of that which is present to be easily recoverable by the plant. For this reason a depleted fine-grained soil would require heavier dressings of soluble fertilizers, in order to have like amounts recovered by the crop in the same time, than would be recovered in a coarse-grained soil.

THOROUGH GRANULATION OF SOILS CONSERVES PLANT FOOD

One of the extremely important functions of the thorough granulation of soils is exercised through its power to conserve soluble plant food. Following an interval without

rain or irrigation, when the soil has dried to a depth, by capillarity, root action or internal evaporation, the soil granules have become more or less depleted of both moisture and salts which the water may have carried with it. These salts have either (1) entered the plant; (2) returned to or toward the surface; or (3) have been left on the outer surface of the soil grains. When a soil in this condition again becomes wet and the water moves downward, the salts are carried forward by both capillary sweeping and percolation, entering the granules again, from which they had been removed, where they are retained against loss from leaching, unless the process is prolonged.

With coarse, sandy soils of single, simple grain structure the case is very different. Here the downward sweeping by capillarity and percolation shoves the soluble plant food forward, leaving behind only that retained within the fixed but very thin films surrounding the individual grains. And even this film, because it is so thin, and because the soil surface is relatively so small,

will be much more depleted than is possible for the films within thoroughly granulated soil, where the surface is enormously greater, and at the same time where the films are chiefly within the granules, removed from the water flowing by.

POROSITY OF SOIL NOT DUE TO STRUCTURE

In nearly all soils, except the very coarse, sandy types, there is a porosity not due to structure, but resulting from the borings of ants, earthworms and other animals and from the deep penetration and decay of roots. Such passageways, in all close-textured soils, are extremely important and advantageous because they greatly facilitate the rapid, deep distribution of water through the soil, allowing the soluble plant food to be swept more readily into the soil granules, while any excess of water is permitted to pass quickly into the underdrainage, leaving less time for such water to become saturated with salts from the interior of the granules. It is extremely important, from the standpoint of conserving soil fer-

tility, that when the soils of a field are saturated with water the distribution should be rapid and uniform and that all excess water should pass out of the root zone as quickly as possible.

To fill the root zone with water, and hold it completely saturated for a number of days, gives the best opportunity for the excess water to extract from the soil all of the plant food it is able to carry, so that, when it passes out, the soil is depleted unnecessarily, unless it should be one which carries an excess of alkalies. There is great danger also, in leaving soils long over-saturated, of the structure being greatly injured by the breaking down of the soil granules. Wherever a soil is thoroughly ramified by deep passageways such as roots and earthworms form, both rain and irrigation water sink deeply and quickly into the whole soil through such passageways and then spread laterally from them by capillarity, thus saturating the soil granules in the shortest possible time, the excess water passing quickly into the underdrainage.

CHAPTER VIII

DEVELOPMENT AND MAINTENANCE OF GOOD PHYSICAL SOIL CONDITIONS

THE growing of any crop must be regarded as essentially a feeding enterprise or problem. As such it differs in no fundamental way from the feeding and maturing of an animal for the purpose of marketing its carcass or the products that may be matured by it. Just as with the animal so the crop to be grown must be placed under those conditions of temperature, sunshine and humidity which through its long evolution have become indispensable to its normal development.

As in the feeding of live stock, it is necessary to supply crops continuously, and in abundance, with a well-balanced ration of food materials that are highly assimilable. It is not unusual to regard a fertile field, in

its power to produce, as analogous to a well-appointed feeding barn fully stored with an over-abundance of food materials of all essential kinds. Such a conception, however, is far from expressing the true relation of a rich soil to the crop maturing on it. The barn is a lifeless storehouse to which animals are brought for a time to mature and be fattened. Not so a fertile soil in which a field of wheat is ripening. Much more nearly does the analogy hold when the comparison is made with animals grazing in a luxuriant pasture of mixed nutritious herbage which grows day by day, now faster and then not so fast, as it is fed away. Within the body of the soil, if it has a high producing power, there are countless millions of living forms, invisible to the unaided eye, which spring into being, pass through life's phases, reproduce their kind and then die. As these flourish on the organic matter, the moisture and the mineral food materials carried in solution and in the air of the soil, they produce, through their growth and through their death, through their interac-

tion among themselves and on the soil, its moisture and its air, food materials in soluble form which are essential to the life of higher plants and which determine in a high degree the immediate productive capacity of soils.

In this light it will be seen that in a very important and a very fundamental sense the soil is a home or habitation in which dwell, in close association, not only multitudes of microscopic life, but the roots of higher plants as well. For the accommodation and the sanitary housing of such communities it is clear that there must be adequate room, abundant water supply and ample ventilation and drainage.

NEEDS OF SOIL VENTILATION

The needs of ample soil ventilation are of the same type and quite as urgent as are those for dwellings and stables where people and animals are housed. It is necessary to supply free oxygen for many of the activities of both roots and the microscopic life

of the soil, as well as for many other oxidation processes. The formation of nitric acid in the soil, which is the immediate form in which nitrogen is supplied to most higher plants, can only take place in the presence of an abundant supply of oxygen. Indeed, if the oxygen is not present in the soil in sufficient quantity, processes are very likely to be set up which will destroy the nitric acid present in the soil in the form of nitrates of lime or other bases, setting the nitrogen free in the ordinary air form.

Ventilation is necessary in the soil to supply air nitrogen for the use of those forms of life which appropriate it and fix it in organic form in the roots of alfalfa, clover and other allied plants, and for other organisms which fix it in the soil. It is necessary to ventilate the soil for the purpose of removing the carbon dioxide which forms in large quantities and tends to dilute the air by its presence, and to change its composition otherwise by the removal of oxygen from the soil air which in part has contributed to its formation.

PROCESSES OF SOIL VENTILATION

The most general and effective process of soil ventilation is that due to the action of wind pressure and wind suction, which drives air into the soil and draws it out by suction in the same manner that it does in dwellings and stables. It is easily seen through the waving of grain and the grass of fields, when the wind is blowing, that the pressure of the wind is never steady, and that it travels in waves of high pressure and waves of low pressure. Under the high-pressure waves air is forced into the soil; under the low-pressure waves it is withdrawn; and in this way, if the soil is sufficiently open, the air of the soil is withdrawn and a fresh supply takes its place.

In all sections where there is a deep, porous substratum, like beds of gravel, sand or dry soil, such as are so extensive in all arid regions, whenever the barometric pressure changes there is a material movement of air into and out of the soil wherever the surface soil is particularly open, the air enter-

ing or leaving such soils and spreading laterally so as to enter or leave those portions which are covered with less pervious layers.

Then there is the general but slow process of diffusion which tends to produce a movement of oxygen into the soil and an escape of carbon dioxide from it so long as there is any difference in composition between the inside and outside air. The effectiveness of this process of diffusion is greatest wherever the soil porosity is greatest and when the temperature is highest. The same process of diffusion tends to produce a movement of the vapor of water into and out of the soil in the same manner that it does in the case of gases, but, just as the loss of water through a mulch, by this process, is relatively small, so is its efficiency in ventilation relatively small.

The entrance of water into the soil, as in the case of rains or irrigation, and the escape of the water by drainage or evaporation, always results in moving like volumes of

air out of or into the soil, thus bringing about soil ventilation.

So long as the temperature of the soil is greater than that of the air outside, it maintains a difference of pressure, operating in exactly the same way to produce ventilation that the heat in a chimney does, and this may have considerable effect, in the hot sunshine, upon the upper layers of the soil.

In order that wind action (which is the strongest factor in soil ventilation) within the root zone may be most effective, it is important, not only that the pore space shall be large in itself, but that the passageways themselves shall be relatively large; otherwise the amount of flow must be small. It must be clear, therefore, that the influence of the physical condition of the soil as a home for the roots of plants, and for the microscopic life which functions there in the interest of crops, is very great, and hence that it is very important to develop these conditions where they are imperfect and to be able to maintain them when once established. These conditions are thorough and deep

granulation and the existence of other passageways leading from the surface through the root zone, such as are left by the decay of roots and by the action of earthworms, and such as are sometimes formed by the shrinking and cracking of the subsoil under excessive drying.

CONDITIONS WHICH FAVOR STRONG GRANULATION OF THE SOIL

1. *Thorough Drainage*

Thorough drainage is one of the prime requisites for deep, strong and permanent granulation. The soil moisture itself is one of the chief factors which tend to bunch the small particles into compound clusters, acting in the same manner that it does in shaping itself into spheres in the raindrop and in the drops of dew on the blades of grass, or as it rolls itself into spheres with the dust about it when sprinkled on a dusty floor. As the soil dries and the space occupied by air enlarges, the soil moisture pinches and draws itself about the soil particles like an

elastic membrane, pulling them together in little clusters wherever there is opportunity to move. As the drying out progresses it often occurs that some of the substances held in solution are precipitated and serve as a cementing material which helps to bind the particles more firmly together.

2. *Dissolved Limestone*

Limestone dissolved in the soil moisture is usually its most abundant ingredient. The waters of North American rivers are estimated to carry more than 400,000 tons in each cubic mile. This dissolved carbonate of lime has a strong flocculating tendency and helps materially to force suspended clay particles into clusters, helping to bind them there and about or within other soil granules, when evaporation concentrates the solution. Because of this strong granulating power exerted by dissolved carbonate of lime, nearly all well-drained soils rich in these carbonates are in the best of physical condition. This being the case the addition of limestone to soils which are deficient in

the lime carbonate will help to improve their physical condition.

3. *Effect of Too Much Soil Water*

The moment a soil has its pore space completely filled with water the binding power of the water on the granules nearly ceases and the compound grains tend to fall apart of their own weight and with the slightest disturbance. The force of expansion which results from the water entering the soil granules, increasing the water films about each individual particle inside the compound grain, also tends to break down the clusters. But if the drainage is so perfect that the air spaces never become completely filled, the water films about the granules remain active and maintain the granules, even though they expand by the absorption of water.

4. *Large Passageways*

It is because of this tendency that such large pores as those due to earthworms and the decay of the larger roots leading down-

ward through the root zone are so helpful in maintaining granulation. They drain the excess water off from the pore spaces, preventing their becoming filled with water and thus maintain the action of the water films about the granules.

We have never seen elsewhere such large numbers of earthworms and those of such enormous size as are found in the rice fields and others in China and Japan. Their action must be extremely important in the drainage of their fields, which are maintained under water continuously from the time of transplanting the rice until the time of harvest approaches. In all of this time ample drainage is maintained and, with it, ample aeration of the soil is secured by the continuous flow of fresh water charged with oxygen. These people are very careful to provide their fields with ample underdrainage, and it is so good that ordinary vegetables, like eggplants, melons, soy beans and even pear orchards, thrive with their roots literally in continuously saturated soil, but in a soil through which fresh water, highly

aerated, is continuously flowing. After the rice season the water is drawn from their fields, and the earthworms, which exist in enormous numbers, begin their work in the soils, which are maintained with a very high content of organic matter, and, during the period of no irrigation and least rainfall, they literally riddle the soil with holes, which favors aeration, drainage and the re-establishment of granulation.

5. *Strong Drying May Improve Texture*

If a very fine clay soil is permitted to dry to a large extent and depth, this drying develops a shrinkage which opens cracks and chinks, often greater than capillary dimensions and often separating the soil into blocks more or less cubical in form. If these blocks are but a quarter or an eighth of an inch in diameter, as is often the case with a clay subsoil, the effect is decidedly advantageous. When such conditions develop efforts should be made to preserve them because of their effect on deeper,

quicker drainage, and on a more uniform distribution of water, and because they may be the beginning of deep and ultimately complete granulation.

When the soil has become thus checked, the addition of limestone, and a good dressing of stable manure—which form a strong soil solution of mineral and organic matter, which may find its way into these parting planes, to encourage the penetration of roots, the multiplication and activity of bacteria, and the granulation of clay particles on the faces of the cubes—will prevent the cubes from rejoining as strongly as before when expansion takes place, so that future shrinkings will again open them more surely and more strongly.

6. *Use of Crops with Dense Root Systems*

When such shrinkage checking has been started in a soil and its subsoil, this is the best time to grow a crop with a dense root system, such as blue grass and timothy have. The throwing of a profusion of fine roots

Fig. 18—Orange groves about Redlands, California.

Fig. 19—Terraced gardens on hill slope. Hayenosaki, Japan.

Fig. 20—View of tea bushes mulched with straw; looking across rice fields in the background. Japan.

into the shrinkage cracks, because of their use of large amounts of water, and because they fill the soil with organic matter, tends to carry the shrinkage still farther and to break the cubes down more completely, thus carrying the granulation a step further toward completion. With the strong mat of roots thus developed, a second year of moderate water content in the soil, so as to insure deep aeration and deep bacterial action and, in the end, stronger drying and further shrinkage, what had been a very close and impervious subsoil will be greatly improved and well started toward the establishment of the best texture.

Lime and stable manure generously applied under such conditions would act to the greatest advantage in improving textural conditions in the soil as well as directly in supplying plant food.

7. *Excessive Drying May Destroy Texture*

From what has been said regarding the action of water in the soil in producing and

maintaining granulation, it may be anticipated that the complete removal of water from the soil would permit an easy breaking down of the granules. This is the fact.

Taking samples of soil in their natural crumb-structure condition, as it came from the field, and screening it through a two-millimeter sieve to remove coarser lumps, it was found, after air-drying one portion and rendering another entirely water-free, that it required, on the average, more than double the time for a given volume of air to flow through the completely dried sample as through the one air-dried, showing that the crumbs had broken down more completely with the withdrawal of all the water. It was also found that, by gently rubbing the air-dry samples in a mortar with a rubber pestle, the granules were so broken down by one treatment that the time of flow of air was increased, on the average, six fold. It was found, further, that after four similar treatments the time required for the flow of a given volume of air had been increased twenty-three fold.

In your very dry climate,* where you develop a mulch six to eight inches deep, it is evident that frequent stirring of such a soil, especially when its temperature is high and therefore the amount of moisture held small, the effect must be to dry-puddle it. Then when water is applied the tendency will be for it to carry the finest soil particles downward below the mulch and through the more open pores of the soil into the deeper layers, tending to form there an increasing impervious stratum which must be injurious in many ways. Unnecessary stirring of soil in such condition as we have described should clearly be avoided, and when such soil is stirred the best time to do it is while it is yet moist, and if repetitions of stirring are needed the doing of this in the cool part of the day would be least harmful in injuring texture.

8. *Effect of Sodium Nitrate on Texture*

Among the many very important soil problems, relating to both soil physics and

*Prepared for the Soil Convention held at Los Angeles, October, 1910.

soil chemistry, which the invaluable work of Dr. Hilgard has solved or illuminated with important light, is the influence of black alkali or sodium carbonate in destroying, more or less completely, the crumb structure of soils. When large amounts of sodium nitrate are used as a fertilizer, to contribute nitrogen to the crop, the appropriation of the nitric acid of the sodium nitrate must set free the sodium, to ultimately find its way into the soil, probably mostly as sodium carbonate which, from its deflocculating tendency, operates injuriously upon the soil, injuring its texture and rendering the soil moisture less available in proportion as it has deflocculated the soil and increased its effective surface for holding water, in the manner which we have already discussed.

This same effect must at the same time retard the capillary and gravitational movement of water in the soil; it must make the aeration less perfect, and it must give the soil power to hold back from the plant larger amounts of the soluble plant food ma-

terials. Thus, while the sodium nitrate may contribute one essential plant food element, and be helpful in this way, it may in other directions be sufficiently harmful to more than counterbalance its influence as a food for plants. Its dangers in this direction are manifestly much greater in arid climates where there is insufficient water to wash the sodium salt from the soil, as takes place readily in all humid climates.

This effect of sodium nitrate in deflocculating soils is strongly manifest in England, especially on the heavy soils, and the Director of the Rothamsted Experiment Station has recently called attention to it as exhibited on the Rothamsted soils. Doctor Hall says, in "Fertilizers and Manures," p. 54:

"One of the most characteristic effects of the use of nitrate of soda as a manure, either repeatedly or in quantity, is its deleterious action upon the texture of a heavy soil; farmers have repeatedly observed that where nitrate of soda has been applied the land remains very wet and poaches badly if it is at all disturbed before it has dried. Market gardeners in particular, who manure heavily with nitrate of soda, have found this destruction of the tilth a serious drawback to its use. . . . Some of the Rothamsted plots in the mangold field, where very large amounts of nitrate of soda have been applied year after year for the last 50 years, show this deterioration of tilth in very marked fashion, the land being intolerably sticky after rain and drying into hard intractable

clods, so much so that it is very difficult to secure a plant of roots unless the season is favorable."

With this effect of sodium nitrate, so strongly marked in a humid climate like England, and sufficiently so that farmers associate the injurious effects with the nitrate, it is clear that the caution here suggested is worthy of serious consideration, particularly on the heavy soils which show any tendency to form hardpan or impervious substratum with irrigation. In such cases nitrogen, if applied, should be in some other form.

Fig. 21—Iris garden and foot-power irrigation near Tokyo, Japan.

Fig. 22—Japanese farm laborers at midday lunch.

CHAPTER IX

FUNCTIONS AND DUTY OF WATER IN CROP PRODUCTION

THE functions of water in crop production are numerous and very important.

1. During the younger stages of growth, and in many cases throughout the life of the plant, water, as such, may form 70 to 95 per cent of the weight of its body substance.

2. Through the photo-synthetic action of light in the green of the leaf, carbon dioxide, entering from the air, and water, entering from the soil, are combined, producing a compound which is the basis of by far the largest part of all the dry substance of plants.

3. Through its solvent action in the soil and in the tissues of plants and animals, water is the medium of transport to and from the tissues of all living forms.

4. In like manner water is the transport medium for the forming and formed substances which are builded into the tissues and products of plants.

It is not strange, therefore, that the right amount of moisture continuously maintained in the soil is an indispensable factor in the production of large yields and in determining the normal quality of the products. Neither is it strange that in earlier times, extending down even to the beginning of the 18th century, the belief prevailed that water was practically the sole food of plants.

But important and large as is the part which water plays in crop production, no statement could be farther from the truth than that, with a proper climate and with the soil in prime physical condition, an abundant supply of water will indefinitely maintain large yields. When the amount of available phosphorus in a soil, or any other food element, is the limiting factor of yield and all the other factors of growth are at the optimum, these will give to the phosphorus its maximum duty in crop production, but, in

the same way, the maximum duty of water, or the minimum amount required per pound of product, will be realized only when all other essential conditions of growth are at the best for the particular crop.

AMOUNT OF WATER REQUIRED FOR LARGE YIELDS

During 10 years, beginning in 1891, we conducted critical experiments to determine the amount of water required to produce a pound of dry substance, including the necessary loss of water by evaporation from the soil, but excluding all loss by drainage. The results were obtained by growing plants in large cylinders, 52 inches deep and 18 inches in diameter, carrying four feet of rich soil. The crops were started with the soil containing the best amount of water, and the cylinders were weighed periodically to ascertain the loss of water which had occurred, this being replaced by watering

Some of the trials were conducted in the open field, surrounded by the same crop, the

cylinders being sunk in pits with their tops level with the ground, and they received the natural rainfall, which was measured. Other trials were conducted in the plant house, where the conditions were more nearly comparable with those of arid climates. For intertilled crops a three-inch earth mulch was maintained, it being developed as soon as practicable after each irrigation.

The mean results of the 10 years' trials indicate that about 450 pounds of water are required to pass through a crop, or evaporated from the surface upon which it grows, for each pound of dry matter produced. The mean yield of dry substance in all of these trials was close to six tons per acre, and the amount of water used was nearly 24 inches, or four inches to the ton.

Six tons of dry produce per acre would be carried

In 24 tons of sugar beets and tops.
In 7 tons of hay.
In 92 bushels of wheat and straw.
In 756 bushels of potatoes and tops.

These are large yields per acre, but entirely practicable under field conditions where the soil is deep, in prime physical condition, abundantly supplied with water continuously maintained.

A more exact statement, upon which these averages are based, is as follows:

AMOUNTS OF WATER REQUIRED BY CROPS IN COMING TO MATURITY, INCLUDING EVAPORATION FROM THE SOIL

Crop	Tons of water per ton of green produce 80% water	Tons of water per ton of dry product	Acre inches of water per ton of dry product
Barley	92.8	464.1	4.10
Oats	100.8	503.9	4.45
Maize	54.2	270.9	2.39
Red clover	115.3	576.6	5.09
Field peas	95.4	477.2	4.21
Irish potatoes	77.0	385.1	3.40
Average	89.25 .78 inch	446.3	3.94

The highest probable duty of water, under the very best conditions, is

21 inches for 70 bushels wheat per acre
15 inches for 70 bushels barley per acre
11 inches for 70 bushels oats per acre
12 inches for 70 bushels corn per acre

Professor Fortier's experiments in Montana have verified these figures for oats, and

the Washington Experiment Station has realized the value set for wheat.

Our experimental value for the duty of water in the production of hay is 17.7 inches of water for four tons. During six years, under ordinary field conditions, we supplemented the rainfall and secured an average of 4.373 tons of hay per acre in two cuttings, with a mean of 19.58 inches of water. The amount needed, calculated from the experimental data, is 19.35 inches.

CONDITIONS WHICH MUST BE OBSERVED TO SECURE THE MAXIMUM DUTY OF WATER

Prime Physical Condition of the Soil

The relatively large yields, at the rate of six tons of dry substance per acre, which we secured in our experimental trials, we believe were due in a large measure to the fact that our cylinders carried four feet in depth of rich surface soil in the best of physical condition, which permitted the roots to spread themselves through the entire depth. In this way the roots were able to have

access to all of the soil moisture, with the plant food it carried. If the physical condition of these soils had been such as to prevent the full occupation of it by the roots, it would have been impossible for capillarity to have brought water and plant food to them with sufficient rapidity to have permitted the rate of growth which was obtained.

As the moisture carried by the soil, under the influence of capillarity, is drawn down by the roots, the rate at which it can leave the soil and enter the roots becomes slower and slower, so that when the roots of crops, because of physical condition, are compelled to develop in a small volume of the soil, the inevitable result is that the soil ceases to yield water, and with it plant food, to the plant with sufficient rapidity to meet the needs of rapid growth before the soil in which the roots are located has been rendered as dry as it might be if the roots were drawing their supply from two or three times the volume of soil. We often saw, in North Carolina, instances of wilting during

the middle of the day, with both corn and cotton, when the second foot of soil and below carried a great abundance of water, but whose physical condition was such, on account of closeness of texture and lack of granulation, as not to permit of the necessary ventilation to induce the roots to enter it.

It is a common observation, in all humid climates, that the deeper soils are almost invariably the most productive ones, and we are satisfied that they are so, in a very large measure, because of the relatively greater root room, which places the plant in contact with enough more soil so that in times of smaller amounts of water they are still able to withdraw a sufficient supply of both water and other plant food to maintain a high rate of growth. Whenever conditions are such that a crop is compelled to stand still for a week or 10 days, especially if it is near the middle of its period of growth, the loss thus sustained can rarely be made good. We often have in our humid eastern climate an unusually wet early season, which holds the subsoil too nearly continuously full of

water, and thus forces a shallow root development, and the surface soil becomes more than normally charged with roots. In such seasons, unless the summer rainfall is more than usually large and well distributed, we invariably secure smaller yields as a direct result of deficiency of water, although the amount present in the soil may have been more than enough for larger yields.

In arid regions such dangers and unfavorable conditions rarely develop except where, through seepage, the water table is forced up into the root zone, or where a close-textured subsoil is so retentive of moisture that over-saturation is unavoidable.

ABUNDANCE OF PLANT FOOD

When the physical conditions of a soil are at the best and the plant food rendered available in it is at the same time sufficiently abundant, the yield is very nearly in proportion to the amount of moisture supplied. It was found in our trials with corn, oats and potatoes planted with the soil in good

physical and moisture condition, where one set of cylinders was allowed to dry out until the crop began to show signs of need of water, while the content of water was held up in the other set to the optimum amount, the yields were:

	Deficient water		Abundant water	
	Yield lbs.	Water per lb. of dry product	Yield lbs.	Water per lb. of dry product
Corn	11,121	246	16,424	275
Oats	8,674	449	18,664	450
Potatoes	7,287	304	12,193	320
Average	9,027	333	15,760	348

With these three crops, where there was a deficiency of water in the soil, the yield was cut down by this deficiency so nearly in proportion to the amount of water supplied that the amount of water per pound of dry matter produced was on the average nearly the same, being, as a matter of fact, 15 pounds less, per pound of dry substance, than it was where the water supply was abundant. This series of observations had another object than that of determining the amount of water required to produce a pound of dry

matter, that being to see how quickly soil exhaustion would follow constant cropping without the addition of fertilizers, and when we compare the water used per pound of dry matter by the first crops on these cylinders with that used by the last crops, both having an abundant and continuous water supply, the results are:

	Virgin soil		Exhausted soil	
	Yield lbs.	Water per lb. of dry product	Yield lbs.	Water per lb. of dry product
Corn	22,313	314	7,666	499
Oats	18,664	450	9,196	800
Potatoes	17,334	301	12,967	576
Average	19,437	355	9,943	625

In this comparison it is seen that although the yield on the exhausted soils was in the aggregate about one-half what it was when the soils were in their virgin condition, the amount of water necessary to produce a pound of dry matter was well up toward double what was required when the soil was in its virgin condition. These observations make it perfectly clear that in irrigated countries, where there is nearly always a

deficiency of water for the lands it is desired to bring under crop, it is of the greatest importance that the best of soil management be practiced, both as regards maintaining physical condition and an abundance of available plant food, for only under these conditions is it possible to realize the largest returns from the water available for irrigation purposes.

UNIFORM DISTRIBUTION OF WATER

There is probably no one difficulty which leads to a low duty of water in irrigation which is so great and so serious as that of applying water uniformly over the entire area. The ideal application of water to a field is realized completely in the gentle, continuous rain which falls at just the rate which permits each drop to enter the soil where it falls without ever saturating completely any portion of the root zone above its capillary capacity, but carrying all parts of it up to that limit. If any method of applying water to the field is devised which

can approach this ideal in all its effect upon the soil, a vast increase in yields will be possible and a large increase in the duty of water will be secured. With such a method of distributing water expeditiously and economically many more acres of land in the arid regions could be reclaimed and most of the losses from seepage and alkalies would be avoided.

When the water is applied unevenly, so that portions of the root zone are oversaturated and adjacent areas receive too little water, the water applied in excess does positive injury by puddling, preventing ventilation, and by leaching, besides being a positive loss in itself. At the same time these losses entail another in the unproductiveness of the portion not watered.

AMOUNT OF WATER APPLIED AT ONE TIME

Another matter which is of the greatest importance in securing large yields, with the highest duty of water, is a knowledge of the best amount of water to be applied to a particular field at one irrigation. To secure

the highest duty of water and to guard against injuries from over-irrigation it is important to know:

(1) The depth of soil which the crop is able to utilize to advantage.

(2) The capacity of the root zone for available water.

A knowledge of these facts, for his own individual field, should be in the possession of each grower before he can determine either the amount of water which it is best to apply at one time or the frequency of irrigation which will give the largest returns. There are few soils where, under proper management, an available depth of four feet for the root zone cannot be secured. It is doubtful, also, whether it is ever desirable to deliberately plan to apply water to more than the surface four feet of soil. Since each foot of soil has a capacity for holding but 4.5 to 6.5 inches in depth of water, when all of the open space is entirely filled, it is plain that the amount of water for single irrigations should always be less than these per foot of depth, where the water is designed

for crop production and not for leaching. It is thus seen that 18 to 26 inches of water can never be applied at one time without overcharging the surface four feet of soil. In the surface four feet of soils in good physical condition the space is occupied by:

23 to 32	inches in depth of soil particles.
10 to 10.8	inches in depth of soil air.
6 to 1.5	inches in depth of unavailable water.
5 to 1.9	inches in depth of available water needed for rapid growth.
4 to 1.8	inches in depth of water to be applied in irrigation.

The available water which soils are able to carry when well drained, in their surface four feet, ranges from 3.7 inches, in the coarse, sandy types, to 9 inches in the clayey and clayey loam types, when these are in good physical condition. Besides this water there is from 1.5 inches to as much as eight inches more carried in the soil but which is unavailable to the crop except as it acts chemically in preparing plant food, and physically in storing the soluble forms of this food upon the surfaces and within the granules of the soil particles.

Altogether, the surface four feet of well-

drained soil may carry enough water to represent 5.2 inches, in the coarse, sandy type, to as high as 17 inches in the most clayey types. When the 3.7 to 9 inches of available water have been exhausted by the crop to below 1.8 to 4 inches, the rate of growth slackens, becoming slower as the limit of unavailable water is reached, when all growth ceases.

Because of these facts irrigation should, if possible, aim to hold the water content of soils between the saturation which gives the lower limit of maximum growth and that of full saturation. When irrigation aims to work between these limits, the amount of water to be applied at one time will vary, according to the texture of the soil, between 1.8 and four inches of water on the level. The water stored in the third and fourth feet of a soil is never as available to the crop as that found in the surface two feet. On this account it is important to keep in mind that the critical exhaustion of moisture is that which occurs in the surface two feet, and that this will almost invariably occur

sooner than does that of the third and fourth feet.

More frequent irrigations, therefore, and smaller applications of water at one time than those we have indicated may in very many cases give the best results. In such cases it will be the water capacity of the surface two feet which will indicate the quantity of water and the frequency of irrigation, and the amounts to be applied at one time may be as low as one inch for the coarsest, sandy soils, and as low as two inches for the more clayey types.

LOSS OF WATER BY SURFACE EVAPORATION FROM SOILS

The loss of water by surface evaporation from the soil, and the cost of restoring and maintaining earth mulches to check this evaporation, are the objections to smaller and more frequent irrigations, which would be made necessary in order to utilize the top soil more exclusively as a water reservoir. We recognize the fact also that arid soils are naturally better aerated, in their

virgin state, than those of humid climates, and that possibly six feet in depth of your soil is no greater from the standpoint of physiological effects than is four feet in the soils of humid climates.* We are speaking now, however, more to the future of your soil problems than to the immediate present, except for those soils which have been longest tilled.

It must not be forgotten that although you are living in an arid climate, nevertheless, by your irrigation methods, you are placing your soils under more humid condition, often, than exists in humid climates, and the ultimate effect must be to develop the characteristics of humid soils, which you will have still to treat under the more severe conditions of your arid climate.

Our own observations in four states, Wisconsin, Pennsylvania, Maryland and North Carolina, show that the evaporation from the surface of a soil kept continuously capillarily saturated with water amounted to an

*This was prepared for the Soil Convention in Los Angeles in October, 1910.

average of 1.84 inches per 10 days. This is 18.4 inches per 100 days, and is enough water for a crop of 60 bushels of wheat per acre. It shows that the loss of water from a continuously wet surface, through evaporation, may be very rapid, even in humid climates.

The loss of water from the Rothamsted drain gauge, which was a naked soil surface through which excess drainage water could be collected and measured, and that lost by evaporation determined, has shown a mean evaporation from the soil surface of 4.78 inches per 100 days between April and September. This is the water equivalent of 15 bushels of wheat per acre.

In Wisconsin the loss through ordinary three-inch earth mulches, under field conditions, is not far from 3.8 inches per 100 days, and is the water equivalent for 15 bushels of barley per acre.

EFFICIENCY OF EARTH MULCHES

The efficiency of earth mulches varies under different conditions:

(1) The efficiency increases with the depth of the mulch.

(2) The efficiency increases with the distance of saturated soil below the mulch.

(3 The efficiency decreases with age.

(4) The efficiency varies with the character of the soil.

In the case of a humus soil, which has the highest efficiency as an earth mulch of anything we have tried, the loss of water by evaporation from the surface when the soil was saturated 19 inches below was at the rate of 5.48 inches where there was no mulch; and one, two, three and four-inch mulches gave evaporations of 3.24, 2.42, 2.20 and 1.89 inches respectively per 100 days.

In the sandy loam, under the same conditions, the loss of water through the no-mulch condition was 6.39 inches, as compared with the 5.48; but the clay loam, under the same conditions, permitted a loss of 15.71 inches in 100 days, as compared with the 5.48 inches loss from the humus soil.

The relative efficiency of the four-inch

Fig. 23—Japanese village with small terraced rice fields in foreground.

Fig. 24—Transplanting rice in Japan.

mulches for the three soils stand, 1.89, 2.22 and 7.78 inches of water per 100 days, the smallest being from the humus soil and the largest loss from the clay loam. When the soil was saturated at six feet below the surface, instead of at 19 inches below the surface, the sandy loam lost water at the rate of but 2.3 inches per 100 days, instead of 6.39 inches, and a clay loam lost but 2.99 inches, instead of 15.71 inches. In these cases the surface of the soil became dry quickly, and acted in the capacity of an earth mulch which is firm instead of one which is loose.

Under the three-inch mulch and with the water six feet below the surface, the sandy loam lost water at the rate of 1.14 per 100 days, instead of 2.38 inches where the soil was saturated 19 inches below the surface. The clay loam under the three-inch mulch lost 2.13 inches with the soil saturated six feet below the surface, where it lost 8.6 inches when the soil was saturated 19 inches below the surface.

When a mulch is developed on the sur-

face of a wet soil the water of the mulch itself is lost very rapidly if the soil has not been too wet when it was formed, and it develops its highest efficiency as a mulch in a comparatively short time. In those cases where, on account of seepage or underflow, saturated soil is permanently within a few feet of the surface, there is often a tendency for the earth mulch to consolidate gradually along the bottom by uniting with the undisturbed soil, and thus diminish its efficiency by practically decreasing its depth. In such cases occasional stirring is desirable in order to increase efficiency. But where there is little water to be brought to the surface from below, and the undisturbed soil gradually dries, the efficiency of the mulch does not usually deteriorate sufficiently to make it worth while to run the risk of dry earth puddling, to which we have referred, by repeated cultivation. When rains follow the development of an earth mulch and tend to destroy it, cultivation should, of course, follow as soon as practicable.

LOSS OF WATER THROUGH CROPS

From the very heavy evaporation which takes place through crops, as is indicated by the number of pounds of water required for the production of a pound of dry matter, it is clear that the chief loss of water by evaporation is through the crop itself, and over this we have little control except through making the conditions of growth the best possible so that the water which is lost through the crop has its highest efficiency.

In the case of a crop of corn which produced at the rate of 5.5 tons of dry substance per acre, the loss of water, from the soil chiefly, during the first 30 days after planting, was at the rate of .29 inch per 10 days. Between 30 and 40 days after planting the loss had increased to .9 inch per 10 days. From the 40th to the 50th day it was 2.19 inches. In the next 10 days it was 2.28 inches, and this was the most rapid rate of loss during the life of the crop. Between the 60th and the 70th days 2.27 inches were

lost, and there were 30 days during which the average consumption of water was at the rate of 2.25 inches per 10 days. In the interval from the 70th to the 80th day after planting the consumption of water again dropped to 1.72 inches, then to 1.13 inches, between the 80th and 90th days; then followed a loss of .92 inch; and again, between the 100th and 110th days, when the crop was mature, the loss had dropped to .88 inch. The crop had thus used, including the loss through the soil, 15.02 inches of water, and of this 15 inches all but 3.19 inches passed through the crop.

This statement has great significance when considering the possibilities of crop production in arid and semi-arid countries without irrigation. It is my judgment that less than one-fifth of the water which leaves the soil in the production of a crop is evaporated from the soil surface under conditions of good management. It is the water which lies in contact with the soil particles, and which afterward passes through the

crop under good conditions for growth, which is effective in producing the crop.

In the case of an oat crop which yielded at the rate of 9.3 tons of dry substance and 227 bushels of oats per acre, the loss of water during the first eight weeks was 6.42 inches; in the next week it was 2.34 inches. During the tenth week the loss was 3.07 inches, then it was 3.10, 2.99, 3.65, 3.59, 4.60, and in the last two weeks, 7.32 inches, a rate only a little less, the oats having been cut when the straw was still green. Thus the crop used in all, during 119 days, 37 inches of water. This amount of water is more than five times the available water which can be stored in the surface four feet of our best prairie loam soil when it carries as high as 27 per cent of moisture, which is about the optimum amount for growth, in such a soil, and the entire volume of water in the four feet of mellow virgin soil in which the crop grew was only 20 inches. It therefore carried less available water than this; probably less than 10 inches could have been made available for anything like a good yield.

FREQUENCY OF IRRIGATION

To make such a crop of corn as has been used in illustration, on a soil like the black prairie loam which will carry 6.7 inches of available water in four feet of depth, and starting with the soil in prime moisture condition at planting, the crop would have used 5.95 inches of water at the end of sixty days, which is nearly the whole available amount of the surface four feet. Hence at this time, if not before, irrigation would be required to the extent of nearly six inches of water. In the next 30 days the crop had again used 6.24 inches, within a third of an inch of all the available water the soil could hold, hence another full irrigation would be required, and this would be sufficient to carry the crop to maturity, as only 2.93 inches more water is needed.

Taking now the crop of oats yielding 227 bushels per acre and using 37 inches of water. If grown on the same soil it would have used 6.42 inches during the first eight weeks, or 56 days, which is almost the full

water capacity of the surface four feet, for available moisture. In each succeeding two weeks the crop used, on the average, a little more than six inches, so that one full irrigation would be required at least as often as once in 15 days.

In the humid soils of the eastern United States it is very rare that a crop does not suffer for lack of water, after it is well started in growth, if the intervals of rain are longer than 10 days. It is seldom, too, that our soils can receive more than two or three inches of rain in as many consecutive days without lowering the yield as a result of over-saturating the soil. We get our best crops and heaviest yields when about two inches of water falls every 10 days and when the rainfall is all in one period covering one or two days.

In our experimental studies regarding the duty of water in crop production, conducted both under field conditions and laboratory methods, the best results were obtained when about two inches of water were applied to loamy soils once in seven to 10 days, after

the crop had reached the stage of active growth.

In the case of a coarse, sandy soil, upon which were grown corn, potatoes, melons and strawberries, critical soil moisture studies, to a depth of four feet, showed that an application of irrigation water, amounting to more than 1.5 inches at one time, produced percolation below the four-foot depth and that in midsummer, if we delayed irrigation more than seven to 10 days, the growth of the crop was retarded.

AMOUNT OF WATER APPLIED IN DIFFERENT COUNTRIES

In Italy, for different crops, the amounts of water used are such that if applied once every 10 days the average depth of each irrigation is 3.39 inches.

In southern France, in the valley of the upper Garonne, water is used at the rate of 2.5 inches, and in the Department of Vaucluse at a rate as low as 1.36 inches per 10 days. In Spain, where the rainfall is less

than in Italy and where greater economy of water is practiced, the average of 19 allotments of water gives 2.35 inches for every 10 days of the growing season.

In Egypt, in winter, the irrigations are at the rate of 3.94 inches once in 40 days, but in summer cotton receives 3.4 inches in 20 days.

An average of 100 cases from all parts of the world gives the duty of water in irrigation at the mean rate of 2.02 inches once in 10 days for a period of 100 days.

CHAPTER X

CONSERVATION AND APPLICATION OF WATER IN CROP PRODUCTION

AS we have said before, the ideal application of water to land is fully realized when it falls as a gentle rain at just the rate which permits each drop to sink at once into the soil where it falls. When this is the case very important results are secured:

(1) The soil is uniformly wet.

(2) The soil texture is improved rather than injured.

(3) The more soluble plant food, which tends to accumulate at the surface through upward capillary sweeping, as the result of evaporation from the soil, is returned to the roots of growing crops. It is practically almost impossible to secure these results by irrigation methods. This makes it all the more important to thoroughly understand

the principles which govern the practices which must be followed.

THE FORCES WHICH DISTRIBUTE WATER IN THE SOIL

When water reaches the soil as rain or by irrigation its distribution through it is effected by two forces:

(1) Surface tension which produces capillary movement such as that causing the ink to enter the blotter, or the rise of oil in the lamp wick.

(2) Gravity which causes the direct descent of water into the soil, always along the line of shortest distance available.

ACTION OF SURFACE TENSION

The surface tension force may move water in any direction, moving it horizontally, upward or downward, sweeping the soil moisture to the active roots, whatever their position, and, with it, the plant food carried. It acts with gravity whenever it

rains or under an irrigation furrow, carrying the water more rapidly into the soil. It acts upward, carrying the water back to the surface just as soon as the surface soil becomes drier than that which is below, the rapidity being greatest when evaporation is strongest and the soil wettest.

In general, capillary flow is always away from the wettest soil toward that which is drier, no matter in what direction that may be. The distance over which surface tension may move water depends chiefly upon the diameter of the capillary pores in the soil, and this is determined by the size of the individual soil grains and by their granulation. If the pores are small, as in the fine-grained soil, the upward movement may be over distances as great as 10 feet in a clay loam. In microscopic glass tubes water has been lifted to measured heights of 100 feet.

RATE OF CAPILLARY MOVEMENT

But the rate at which surface tension is able to move water is relatively very slow under the best conditions, and it is for-

tunate that it is so, for otherwise the loss of water from the soil by surface evaporation would be much greater than it is. We have measured a capillary flow of water vertically upward through a foot in depth of soil, giving a rate of:

2.37 lbs., or .45 inch per square foot per day in fine sand.
2.05 lbs., or .39 inch per square foot per day in clay loam.

When the water was lifted through four feet of wet soil the rate of capillary rise was reduced to:

.91 lb., or .175 inch per square foot per day in fine sand.
.90 lb., or .173 inch per square foot per day in clay loam.

But when the soil was dry the rate of vertical capillary rise into one square foot of soil one foot deep was no faster than it was through four feet of the same type of soil fully saturated, or .16 inch per day.

This is the mean for 24 days, the soil not having become saturated until sometime during the eighth three-day period. During the first three days, however, the soil had taken up 12 pounds of the 19 which the cubic foot of soil finally acquired, some 20

days being required for gaining the other seven pounds.

But the rate of capillary movement horizontally in dry soil is more rapid and about the same as that in fully saturated soil of the same type or, in this case 2.4 pounds, or .45 inch per square foot per day in clay loam.

These are fundamental facts which may be made to serve in guiding the application of water for irrigation. The rates I have given for the upward and horizontal movement of water through soils, while they seem rapid when we consider their influence on the loss of water from soil, they are in reality not so large when viewed from the standpoint of applying the surface tension force in saturating soil with water through capillary action.

Suppose we are considering the question of deep and shallow furrow irrigation and the best distance apart for the furrows, together with the length of time required to evenly distribute a given amount of water through soils. To obtain quantitative data bearing on such questions, we removed col-

umns of soil one foot long, by means of metal cylinders, without disturbing in any way the natural field textural condition and, after drying the soil, set the bases of the columns in one inch of water, under conditions where evaporation was prevented, and weighed the soils at intervals of three days to obtain a measure of the rate of upward capillary rise of water into them. At the end, when saturation had been complete, we had results like these:

8th three days	.07	pound per square foot.
7th three days	.12	pound per square foot.
6th three days	.44	pound per square foot.
5th three days	.96	pound per square foot.
4th three days	1.33	pounds per square foot.
3d three days	1.74	pounds per square foot.
2d three days	2.57	pounds per square foot.
1st three days	12.50	pounds per square foot.
Total,	19.73	pounds = 3.79 inches.

It was six days before this soil showed the first signs of moisture at the surface, yet all of the time standing in an inch of water and where there was no evaporation. It was at least 21 days before capillarity had completely filled the soil as rain would have done, or surface irrigation.

It is important to note the very great difference in the rate at which water entered the soil during succeeding periods and to understand the cause of this. With each inch of rise of water in the soil the lifting force of surface tension is decreased by the downward pull of the pressure of one inch of water and, as the lifting power of the surface tension remains constant, the rate at which water can be lifted by it, in such a case as this, must be a decreasing one. Then there is a second cause for the decreasing rate of flow, and this operates in whatever direction the water may be moving, whether upward, horizontally or downward, and it operates in the same way against the gravity pull as well as against the surface tension pull. It is like pulling a string through an opening against which it drags. If there is an inch of surface contact on the string, there is an inch of drag, and this reduces the effective pull by so much; if there are two inches of surface contact, there are two inches of drag, and double the resistance must be overcome. The principle is the

same in the movement of water through soils, when the movement is through the capillary pores.

If water is moving horizontally by capillarity away from under an irrigation furrow, the resistance to be overcome in carrying the water through the second inch is double what was necessary to carry it through the first inch, and hence the progress made in the second inch will be slower than that made in the first inch, and hence, as the distance between furrows is increased the drag on the water becomes so great that ultimately a dry area must be left between furrows, and for the same reason that when ground water is a certain distance below the root zone water cannot be lifted by capillarity into the root zone.

These statements make it clear also that if one were trying to saturate the surface foot of soil by upward capillary movement by means of water carried in tile with their tops laid one foot below the surface, it would be impossible to do so without great loss of water by downward percolation, un-

less there were some impervious layer not far below the tile.

TIME REQUIRED FOR LATERAL SPREADING

To measure the time required to saturate the soil by horizontal capillary spreading, we filled a six by six foot tray, eight inches deep, with a clay loam, firmed to the density of field conditions. In one corner of the tray was set on end a section of six-inch drain tile. In the bottom of this, water was maintained at a depth of three-fourths of an inch, automatically, in a manner which permitted weighing periodically the water which entered the soil. It was found that at a distance of one foot from the tile water moved horizontally at the rate of 3.73 pounds per square foot, or .46 inch per day, during 44 days; that eight inches of soil became saturated at one foot from the tile; and that no water passed into the soil beyond a distance of 3.5 feet from the tile, the soil beyond this distance becoming increasingly drier than when the experiment started. It is clear

from these observations that in furrow irrigation water cannot be economically applied unless the furrows are pretty close together.

It is not likely that the drag of 3.5 feet on the streams of water moving horizontally through this particular soil was sufficient to entirely overcome the surface tension pull. What did happen was that the rate of capillary movement upward to the surface and evaporation from the surface prevented any moisture being carried farther than 3.5 feet from the furrow. Of course, the same limiting conditions must always be effective in a field, even though a good mulch exists. for these do not prevent all evaporation

A SPECIFIC CASE

Let us take a specific case where the furrows are laid say three feet apart, deep and broad enough so that gravity flow directly downward beneath the furrow saturates one foot in width of the soil. In such a case one-third of the field would be irrigated by the directly downward gravity flow and

two-thirds of the field would have its soil moistened by the horizontal capillary flow.

RATE OF PERCOLATION DOWNWARD

In the coarser, sandy soils the rate of gravity flow may be relatively very rapid, many times exceeding the capillary flow in ordinary soils. We have measured the gravity flow downward through five rather coarse sands, and through two soils, one a sandy loam and the other a clay loam. These are the rates of movement through the sands and soils, expressed in inches of water which passed into columns eight to 10 feet long, per day.

	No. of grains per linear inch	Inches of water per day
No. 20 sand,	54	492
No. 40 sand,	138	362
No. 60 sand,	164	272
No. 80 sand,	215	72
No. 100 sand,	307	58
Sandy loam,	1,554	3
Clay loam,	2,026	2

From the rates at which water entered the sandy loam and the clay loam it ought to be possible to apply two or three inches

of water to a field and have it all enter the soil during 24 hours, if the movement were directly downward, due to the gravity pull alone.

In Dr. Loughridge's studies, made at Riverside some years ago, it was found, where irrigation was maintained during 72 hours in furrows three to four feet apart, and where 4.5 inches of water were applied, that the average depth of penetration of water was about four feet and the distance the water had spread laterally averaged only about 2.5 feet. Besides this, much of the soil received no water, while very large amounts of water had percolated below the depth in which the roots had developed.

It ought to be possible to apply water to an orchard and much more nearly realize the conditions which follow natural rainfall than was secured here. Let us go over carefully the method by which water enters the soil and then point out how it appears possible to secure a quicker and more uniform distribution of the water.

When water is admitted to the furrows,

the immediate effect of gravity is to cause the water to sink at once directly downward, displacing the soil air, causing it to flow sidewise and escape upward through the pores of the soil between the furrows. It must be kept in mind that, before water can enter a soil, the air it contains must escape, as must be the case in filling a bottle or a jug. The chief reason why there is so much surface washing and flow of water over the surface, in times of violent rainfall, is the complete sealing up of the soil pores at the surface, so completely preventing the escape of soil air that the water is prevented from entering.

In climates subject to heavy rainfall, as in parts of China, farmers have learned to plant on narrow level ridges with narrow furrows between, which draw the water quickly to the bottoms of the furrows, thus preventing portions of the surface from becoming flooded, leaving opportunity for the water to sink quickly into the soil and spread laterally under the ridges as the air escapes, thus preventing washing and securing the

retention of the rainfall more evenly over the surface and a quicker deep penetration into the soil.

When rain falls gently, the pores of the soil are kept open by the water entering almost entirely by capillary action, which keeps the pores open, allowing ready escape of the air. One of the advantages of the deep irrigation furrows over the shallow ones is that they require a much longer time before capillarity saturates the surface soil, thus preventing shutting off the escape of air before the lower soil has become moistened by lateral capillary flow. When water is admitted to shallow furrows lying wholly in the earth mulch, which is very much more open than the undisturbed soil below, the water tends to spread laterally by both gravity and capillary action along the under surface of the mulch, thus sealing over quickly the air passages leading from the deeper soil, so that a direct resistance is imposed, hindering the sinking of the water directly downward and the moving of it laterally under the surface tension pull, this

resistance being the air which cannot readily escape. But if the irrigation furrows are cut below the mulch, not only is the danger referred to avoided or made much less, but the efficiency of the loose soil to act as a mulch is not nearly so much lessened by becoming quickly over-saturated. In this way a large saving of water is effected by lessening the surface evaporation, and deeper, more uniform distribution is secured.

Over-saturation of the immediate surface soil by either flooding or too strong capillary action should always be avoided on naked soil. If the surface is flooded, the texture of the soil is greatly injured, and if too strong upward capillary movement takes place much of the soluble plant food, which should be left below the mulch, is carried to the surface where, for the time being, it is useless. When air can escape readily from under the furrow the water drops rapidly. At the same time capillary action draws the water out laterally and we have the conditions desired.

When the water has dropped another

foot, it has also spread laterally and, finally, the capillary streams from the adjacent furrows have met. But now, if the soil is in good textural condition, the meeting of the capillary streams will not entirely lock in the air, even if meeting does take place, because the normal effect of the surface tension pull is to draw the water into layers surrounding each granule, the water soaking into the granules or being held in thicker layers around them, thus leaving openings between the grains as before, except that they are of smaller diameter.

After the capillary streams have met in the middle, gravity begins to act with capillarity under the space between the furrows, to turn the water downward, thus hastening the filling of the soil below through the continued capillary action above the level where the capillary streams have met.

The important thing for the irrigator to learn regarding his own particular field is how rapidly the water may be made to descend and spread laterally so that the whole soil between the furrows has become

sufficiently wet at the time that the water, moving directly downward, has reached the bottom of the root zone, thus enabling him to give his irrigation furrows the proper depth and distance apart.

BEST DEPTH OF SATURATION OF SOIL

We doubt if it is desirable, even in your* arid climate soils, to saturate by irrigation beyond a depth of four feet except at those times when it may be desirable to produce leaching for the purpose of removing accumulated alkali. There is always a very slow downward movement of the capillary water until the soil becomes much drier than is best for rapid growth.

We found, through a study of columns of sand 10 feet long, arranged so that percolation could take place from the bottom, but with their surfaces covered so as to stop evaporation, that water did not cease to drain from them until after a period of

*This was prepared for the Soil Convention in Los Angeles in October, 1910.

more than two years. In a very short time practically all of the free water drained out, but after this there was a gradually decreasing drainage kept up for a long time.

Because of this condition we are satisfied that a sufficient amount of water will be maintained at any desired depth below four feet if the water in the surface four feet is maintained in sufficient amount for best growth.

Because it often requires many hours for the irrigation stream to reach the lower end of the furrow, a sufficient amount of water in the upper end of the furrows has entered the soil long before the required amount has been received at the lower end. And before the lower end of the area being irrigated is sufficiently watered there is much loss from seepage at the upper end, thus entailing expense to the irrigator and subjecting lands lying at lower levels to injury from water-logging and the bringing up of alkalies which the percolation from rains at earlier times may have carried far below the surface.

TWO WAYS OF SECURING MORE EVEN DISTRIBUTION OF WATER

There ought to be ways of applying water which shall more generally avoid the waste and the dangers to which we have referred, applying the water so that there shall be no excess at either the head ditch or at the foot of the furrows. There are two ways which appear to us practicable of avoiding the evils and of securing a much higher duty of water, and neither of them, so far as we know, are systematically practiced to any large extent.

(1) *Use of level furrows*

When irrigation furrows are eight to 12 inches deep, the necessary head for distributing water through them over quite long distances can be provided when they are perfectly level, by the depth of four to six inches of water in the furrow. Suppose a 10-acre orchard is to be irrigated. By laying the irrigation furrows across the slope rather than down the slope, making

them level, the water may be led down one or both sides or down the middle and turned into the level furrows instead of leading it across the upper end, as is the more general practice. With the level furrows water would be taken out in sufficient volume to fill the furrow quickly its entire length to a depth of four to six inches, then the supply would be cut down sufficiently to just maintain the water in the furrow at about this depth. Succeeding furrows would be similarly filled until the supply of water is brought into service.

With such a method of distribution there would be perfectly uniform penetration of the water throughout the length of every furrow, so far as the texture of the soil would permit. No part of the furrow would be longer under water than another, and each furrow is entirely independent of every other; water could be stopped in any furrow at any time; or, if one end of the furrow is in more open soil than another, water could be shut off from that portion, leaving it on the other. There would be no need of

wasting water at either end of the furrow. Such a method of applying water would require a materially shorter time to saturate the four feet to the desired degree.

When the water runs in a narrow stream along a furrow, leaving a broad strip on each side of the stream only capillarily saturated, the water cannot penetrate downward nearly as rapidly as it can when a wider surface is under free water. This is so because the surface which is under the capillary water is under the action of an upward capillary pull, tending to lift the water to the surface, and this upward pull acts against the downward pull of both gravity and surface tension, diminishing their effect by the amount of the upward pull.

On the other hand, when the bottom of the furrow is under six or eight inches of water, this upward pull is not only entirely eliminated, but we have the pressure of the free water itself as an added force to aid in rapid descent. The water, therefore, goes faster downward and is brought more

quickly to where the lateral capillary pull may draw it sidewise between furrows.

By such a method, therefore, less time is required to wet a given area thoroughly, and the water is saved by being able to restore the mulch earlier and thus check the evaporation which takes place from wet soil and water. Besides, while water is being applied, the evaporation is much more rapid from a saturated soil surface than it is from a free-water surface, the soil being much warmer under the action of the sun than the water.

The rate of evaporation from a water surface west of the 103d meridian, as shown by a large number of measurements, averages .21 inch per day, while the evaporation from a wet soil surface has been found to be as high as an inch in three days. East of the Mississippi the evaporation from a free-water surface between April and October averages .14 inch per day, a third less than in the West, and the evaporation from a wet soil surface is .18 inch—scarcely more than half what you may have here.

It appears to me practicable to apply sufficient water for one irrigation, wetting to a depth of four feet, by such a method as this, in 24 hours or less for most soils and to entirely avoid loss from seepage, while at the same time there may be a large saving from excessive surface evaporation. In addition there would be gained the most important advantage of all, a more uniform distribution of the water through the soil.

(2) *Crop Mulch Method*

The second method which I wish to present may be called the crop mulch system, or the fertility and good tilth maintenance method.

I have before indicated that you have immense stores of the plant food elements in the surface four feet of your soils, and that it must become the business of agriculturists, sooner or later, to transform and use these stores in the production of crops much more extensively than present practices insure. I have also indicated that it is extremely im-

portant that in some manner the textural condition of the soil shall be maintained right against the destructive tendencies which are inevitably associated with years of naked culture and repeated irrigation. And so I believe it would be a very great gain if the growing of alfalfa could be effected on strips between the rows of orchard trees and the crop so grown used as a mulch and a fertilizer, covering the strips under and between the trees where the alfalfa is not grown.

If it is practicable to grow alfalfa or some functionally similar crop, either continuously or periodically, on strips, say 12 feet wide, in the center between the trees, extending down the slope, water could then be led in furrows down each side, watering the alfalfa by flooding and the tree rows by seepage and capillary spreading, or by occasional flooding if that seemed called for. The crop could be cut and spread as a mulch and fertilizer dressing over the intervening space and under the trees, taking the place of regular tillage to prevent evaporation,

and gradually decaying and leaching, under the influence of winter rains and occasional flooding, it would supply soluble potash, phosphorus and lime, as well as nitrogen, directly under and between the trees, over the entire mulched strip.

At the same time the deep penetration and strong root development of the alfalfa, on the middle strips, would give you the best possible subsoiling effect, developing a type of openness favorable to the distribution of water and the deep penetration of air, difficult to procure in any other way. The decay of the organic matter left in the soil, through combined root and bacterial action, would render soluble the stores of potash and phosphoric acid deep in the soil, to be brought up by the alfalfa plants and transferred to the mulched strips for the use of the trees, or the spread of the roots of the trees under the alfalfa would permit them to utilize the soluble salts directly.

Such a combination would give you a means of maintaining a sufficient supply of organic matter in the soil, which is indis-

pensable to the most economic fertilization and which your present methods of maintenance of dry earth mulches must tend rapidly to reduce.

In Japan we saw extensive tea orchards and pear orchards heavily mulched with rice and other straw and with leaves and grass. In these cases, sometimes on steep sloping areas, the rains leached the fertility, in the form of soluble ash ingredients, directly out of the straw. At the same time the straw acts as a mulch and dispenses with the necessity of using any part of the soil itself for this purpose. Moreover, it prevents surface washing and compels the rain to enter the soil directly where it falls, thus making it more efficient because of its even distribution as well as because of its conservation. Gradually this organic matter decays, most rapidly from its under surface, forming a mold and humus which in time nitrifies and supplies this element to their crops.

If this method can be successfully developed in your orchards, it would do away

with the expense of maintaining surface-deep earth mulches and, in my judgment, you would find the practice to require less water than your present methods do. You certainly would not be required to supply nitrogen in the form of Chili saltpeter, which is objectionable from the standpoint of its tendency to develop black alkali, of which you have an excess developed inevitably as a result of soil weathering, with deficient rainfall to wash it away.

If such a method is practicable and profitable it quite likely would be found desirable to practice it as a rotation with a dry earth mulch treatment which you now so generally practice, thus giving complete opportunity for the decay of the roots of the alfalfa and the spread of the tree roots into the space occupied by the alfalfa. It might even be desirable, where the slope of the land permits, to change the direction of the seeding so as to occupy the soil between the rows in the other direction, thus improving the texture and charging the soil of the whole orchard with the roots.

It seems to me that such a method would effectually prevent and tend to destroy all hardpan forming.

CHAPTER XI

RECLAMATION OF SWAMP LANDS

THERE are certain general principles and facts underlying the reclamation of all lands of whatever sort by underdrainage which should be thoroughly understood and kept clearly in mind, not only by those who contemplate such reclamation, but also by those who think of purchasing such lands for agricultural purposes after they have been partly or completely drained.

1. All "water-logged" soils and subsoils are agriculturally more or less unproductive except for some few special crops which are adapted to such conditions, and, primarily, because they are "water-logged." This must be generally true, too, regardless either of the absolute amounts or of the availability of the plant food elements or of the plant food present in the soil. The roots of very

few agricultural crops can penetrate water-logged soil.

2. Complete and rapid underdrainage is one of the prime essentials to both the development and the maintenance of the highest productive capacity of any field or soil. When the subsoil is open and the distance to the water level beneath the surface of the field is six or more feet at all times of the year, the excess of water after even heavy rains quickly drops below the level at which roots feed and where plant food develops. Under such conditions the evil effects of water-logging are not felt and the soils develop plant food rapidly and retain it against loss by leaching far better than where water-logging or complete saturation is possible.

3. In fields that are naturally underdrained, that is, where the water level in the ground never reaches nearer than within six feet of the surface, and where the surface soil is properly open, it is only necessary for the excess of rain to flow directly downward under the full effective pull of gravity

through the short distance of six feet to pass beyond the place where it can do harm to crops.

4. But where open ditches must be dug or underdrains laid in order to remove the excess of rains from the soil, this excess must not only percolate down through the surface soil, just as in the naturally underdrained fields, but in addition to this it must flow horizontally greater or less distances in order to reach the surface ditches or underdrains. It is clear, therefore, that even when drains are laid as close as 30 feet, much of the excess water must not only travel more than 15 feet before it leaves the feeding and food-producing portion of the soil, but it must travel through this longer distance under a small fall or pressure. The time required for the removal of the excess of water must therefore be much longer than where soils are naturally underdrained. In regions of frequent and heavy rainfall it will be clear that there is danger of fields, even after they have been well underdrained, becoming water-logged for several

days in succession, and, therefore, of having their productive capacity reduced from the effects of insufficient underdrainage.

5. When open ditches have been dug or underdrains have been laid in a field, these are seldom able to effectively drain the soil to the level of the bottom of the drains. Besides this, the capillary power of soils for lifting water is so strong that, in all except those which are extremely coarse grained, the spaces between the soil grains are maintained too nearly filled with water for six inches to a full foot or even more above the bottoms of the drains to permit the roots of crops to penetrate to nearer than these distances above the bottoms of the drains. Lands requiring underdraining to make them productive, therefore, are not affected by the drainage system as deeply as the drains are laid.

6. It has seldom been found economically practicable to lay any but main drains more than four feet deep as a general average for the field and, since the efficiently drained portion of the soil lies six to 12 inches or

more above the bottoms of the drains, a tile-drained field must possess a smaller depth of soil and subsoil in which soil organisms may multiply, where plant food may develop and where the roots may feed. It is seldom true, therefore, that when any field has been improved by artificial underdrainage, it is rendered as productive as other fields naturally and amply underdrained, carrying like amounts and kinds of plant food elements as readily convertible into forms available to crops.

7. It is true that where lands are not naturally sufficiently drained for agricultural purposes their productive capacity may generally be very much improved by underdrainage, and even when this is done to depths less than four feet, but to what extent lands will be improved by underdrainage, and whether or not the improvement will pay for the expenditure depends upon the inherent quality of the land, upon the expense required to bring it into tillable condition and upon the use to which it is to be put.

Fig. 25—Pumping water for irrigating rice fields. Japan.

Fig. 26—Chinese rice paddies at transplanting time.

Fig. 27—Grove of small bamboo with earth hilled up about the roots to favor the development of bamboo sprouts which are so extensively used for food in China. The mounds about the trees are some two feet and three feet in diameter.

8. There is an extremely wide diversity in the quality of marsh and swamp lands. Such swamp lands as are built up by the overflow of great rivers, like the lower Mississippi, which results in an intimate commingling of organic matter with rich mineral soil ingredients, forming deep, broad flats, are among the richest and most enduring soils in the world when they are drained to an ample depth. On the other hand, the peat swamps which have developed back from the river courses, especially over the lake bottoms in wooded districts where but little silt or other solid soil minerals have been mingled with the accumulating and decaying vegetation, so that beds four or more feet in thickness have been formed and still remain brown and peaty in character, give us a type of one of the poorest soils, if, indeed, it is entitled to the name of soil, not excepting the " sand barrens," so called. Between these widely separated extremes in types of fresh-water swamp lands, formed in humid climates, there are all gradations and to classify the lands cor-

rectly and closely as to their relative agricultural values, even after a careful study on the ground, aided by the best expert and practical knowledge, remains up to today an extremely difficult if not impossible task.

WEIGHTS OF SWAMP AND PEAT SOILS

If we compare the dry weights of swamp and peat soils with those of other types, they stand, in round numbers, approximately as given below:

Coarse, poor sandy soil, surface foot	1,950 tons per acre.
Fine, loamy clay soil, surface foot	1,400 tons per acre.
Black marsh or muck soil, surface foot	980 tons per acre.
Heavy peat soils, surface foot	430 tons per acre.
Light peat soils, surface foot	200 tons per acre.

It is clear from this table that a very wide difference exists between both heavy and light peat soils and the soils of the better types, and it is very important to keep these differences in weight of the soils in mind whenever percentage amounts of plant food carried by them are being considered, for it is the basis upon which must be computed the total amounts of plant food elements,

and of plant food proper, carried by them. The light peat soils, for example, weighing but 200 tons per acre-foot, might have an analysis showing in per cent ten times as much potash, phosphoric acid or nitrogen as that indicated for the coarse, poor sandy soil and yet carry but little more of them per acre. The same must be true so far as soil moisture is concerned. The peaty soils carry, when expressed in per cent, very large amounts of water, but, because of their light weight, the absolute amount is not as great as it appears, and besides this, a very large per cent of that which is carried by them is wholly unavailable to crops.

AMOUNT OF PLANT FOOD ELEMENTS IN PEAT AND SWAMP SOILS

We have taken occasion to go over the more recent data collected, both in this country and in Europe, showing the amounts of plant food elements carried in a surface foot of peat and swamp soils, and a

portion of existing data relating to these soils are given in the next table:

	Potash K	Lime Ca.	Phosphoric acid P	Nitrogen N
	Tons per acre in surface foot.			
Good average soils	20	8.9	2.4	4
Black marsh soil, Wis.	11.5	12.6	.98	3.4
Poor sandy soil	4.6	5.3	.79	.9
Peat soil, Wis.	1.5	6.3	.44	10.8
Michigan celery peat	1.9	25.5	2.1	9.6
*Minnesota "Muskeg" No. 1	.5	1.2	.38	11.6
Minnesota, No. 294	1.8	2.5	.97	4.3

Of 88 analyses of Austrian peat soils, published this year, and grouped in three classes, the analyses show the following amounts calculated to one foot depth:

	Weight of dry peat	Potash K	Lime Ca.	Phosphoric acid P	Nitrogen N
	Tons per acre in surface foot.				
High moor	135	.09	.5	.06	1.7
Mixed moor	273	.23	2.7	.15	4.5
Low moor	408	.33	8.6	.29	9.5

So, too, in 143 Bavarian peats, analyses for amounts of potassium found in the surface

*These are peat swamps formed back from the rivers in the woods, and which are yet covered with thick growth of sphagnum moss and dwarf black spruce.

foot, classified in eight groups, showed, for the averages, from only 104 pounds to 608 pounds in the surface foot of an acre, and the peats of the lightest group weighed but 150 tons, and those of the heaviest group, 430 tons per acre. These analyses from both this country and in Europe show that the peat soils proper, when compared with good soils, are relatively very deficient in the essential plant food elements other than nitrogen. The black marsh and muck soils, although not always productive when reclaimed, and although often found deficient in available potash and phosphoric acid and sometimes lime, are, nevertheless, very much more hopeful soils.

How little mineral matter peats may contain, and how far they really differ from true soils, can best be understood from the statement that 21 of the 88 Austrian peats cited have an average ash content of but 3.36 per cent, and 41 of them, almost half of the whole number, but 5.77 per cent, while only three out of the 88 showed an ash content above 50 per cent. the highest being

59.70. The contrast between these and true soils may perhaps be made more striking when it is stated that the average ash content of the straw of maize, wheat, oats, barley, rye and clover averages 4.75 per cent and that of stable manure 5.52 per cent. These averages are of the same order of value as those shown by the 21 and 41 averages for the 88 Austrian peats, and the comparison shows that the reclaiming of these types of lands for agricultural purposes is not wholly unlike trying to cultivate fields deeply covered with decaying straw or average farmyard manure. They must be regarded as very special and peculiar soils, requiring special treatment and adapted only to special crops.

Where the peat deposits are less than three feet deep, and underlaid by a good subsoil, the prospects are fairly promising if there is an ample lime content to keep the organic acids neutralized. It must be remembered that the organic matter will shrink much as it comes to decay, and due allowance must be made for this in draining.

Where there is a thin layer of peat not well decomposed, underlaid by a highly siliceous sand, there is both a poor surface and a poor subsoil, which must in time become the surface soil. An effort has been made in Minnesota to reclaim such lands as the "Muskeg" named in the table, but, after draining, scalping and clearing in 1896, blue joint only came in to grow well in 1902, and this was in only one place where the subsoil was within 18 inches of the surface, the organic matter at 20 inches being only 46 per cent, and at 10 inches 86.4 per cent. Where the high content of organic matter extended to a depth of 30 inches the grasses did not develop.

In marshes of the deep peat type, when the growth of such deposits has extended so far that the whole basin has been filled to the bottom, the further accumulation of the peat materials receives a check and the processes of decay may set in, resulting in developing a layer over the top whose ash content increases, partly because the purely organic matter passes away, and partly from

dust accumulations from the air or in washings from the surrounding higher lands. This decay is hastened by drainage, so that in the course of time there may be developed over these deep peat marshes a surface layer approaching the black marsh or muck type which permits the sweet grasses to grow and changes the marsh from one class into the other. It is clear, however, that before such accumulations can take place either some inwash from adjacent regions must occur or else a large subsidence of the surface must result from the loss of organic matter, so that tile laid at four feet might in time come to be very close to the surface. But the formation of a more fertile layer over the top, leaving the matter of subsidence out of the question, must necessarily require a long time unless hastened by methods involving considerable expense.

The black marsh or muck type of swamp soil, containing much clay and sand, with a smaller per cent of organic matter, such as is represented by the analysis given in the first table, although much richer inherently

than the peat types, is yet relatively deficient in potash and phosphoric acid when compared with the best types of upland soils so that, aside from having less available depth, because they require underdrainage, they will necessarily require the addition of these fertilizers more persistently than the best class of soils will, and the statement applies with increased force to reclaimed peat soils after they have been brought to the productive stage. Both types are therefore best adapted to intensive types of culture, where the character of the crop grown warrants high fertilization.

Neither of these types of soil are as a class well suited to the growth of alfalfa or of the clovers generally. Alfalfa does best, and the clovers, too, on deep, open, well-drained soils rich in lime. This, however, is to be said, so far as the need of these soils themselves is concerned, they are so inherently rich in nitrogen that for a long time there would be less need of clovers in the rotation to keep up the nitrogen supply.

CHAPTER XII

AGRICULTURE OF THREE ANCIENT NATIONS

THE attention and effort which have for centuries been devoted to the maintenance of soil fertility in China, Korea and Japan are probably greater than in any other part of the world, and the efficiency of these efforts is measured by the dense populations these countries have maintained and are still maintaining largely from the products of their soil. Probably nothing can give a safer measure of the maintenance capacity of the farms and farmers of a nation than the number of people they feed per unit area of cultivated field, and it is doubtful if there is a better place to study this problem than in China and Japan at the present time.

We were most of all interested in methods of tillage, of fertilization, and crop rotation.

We wanted to learn by seeing how it is to-day possible, after 20, 30 and perhaps 40 centuries, for their farmers to provide means of maintenance for such dense populations as now are living in these three countries. During the long maintenance of dense populations the people of these nations have grown into practices of economy and habits of industry the equal of which few people of western nations have attained or are likely to appreciate. While we may never adopt the details of any of the methods of these people, it is worth our while to study carefully some of those they have practiced so long and found eminently satisfactory under their conditions, because of the fundamental principles involved, and because they may suggest modifications of some of our practices or adaptations of theirs which may be helpful to us.

One of the most fundamental differences between our cultural methods and practices and those of the Far East is found in the fact that there, as nearly as possible, every day in the year the soil, the climate and

the people are crowding growth. In nearly all parts of the densely populated sections two, three and sometimes even four crops are taken from the same field each year. This is made possible partly by their more favorable geographic position. Southernmost China has the latitude of Cuba, while to the north, Mukden, and northern Honshu in Japan, are only in the latitude of New York, Chicago and northern California. The United States lie mainly between 50 and 30 degrees of latitude while China, Korea and the densely populated portions of Japan lie between 40 and 20 degrees, nearly 700 miles farther south, giving them longer and warmer seasons.

But this is not the only cause of their longer growing season. The almost universal practice of planting nearly all crops in rows and in hills in the row permits one crop to be planted, germinated and often hoed before another crop has been removed from the field, thus utilizing for growth all of the time we consume in removing the harvest and in fitting the ground for the

next crop. As an illustration of this, there is a crop of barley nearly ready to harvest, a crop of Windsor beans which will come off the ground in a month, and there has just been planted between the rows of barley a crop of cotton. The land is first fertilized, plowed and fitted and planted to barley, usually on ridges four feet wide. After the barley is up, has been once or twice hoed and perhaps fed with liquid manure, the ground is fitted on the outside of the bed and planted to Windsor beans. Then when the barley is so far matured that it has ceased to draw fertility from the land other than moisture, the ground between rows of barley is fertilized and fitted for cotton, the cotton planted and by the time the barley has been pulled the cotton is up and has been once hoed. When the barley is out of the way, the cotton will receive its cultivation until the Windsor beans are ready to harvest. These will then be taken off the ground, the ground fertilized and fitted for some fall crop. By adopting this method they are able to keep both themselves and the land

fully occupied every moment of the growing season.

Then there is the other very extensive practice of starting crops in nurseries under conditions of intense fertilization, securing on a much smaller area rapid growth and strong plants, which are then transferred to the fields. In this manner even the vast areas covered by the staple rice crop are handled, the plants being grown 30 or more days in small beds, gaining thereby 30 to 50 days during which another crop on the same field is matured, harvested and the ground fitted for the one to follow. Human labor is the one asset of which they have an excess, and it is freely used in securing the effect of longer seasons, which, because of their geographical position, exceed ours. In southern China, two crops of rice are regularly taken, and this is true even in parts of Japan. In the Shantung province a crop of winter wheat or of barley is followed in the summer by a crop of millet and soy beans, of sweet potatoes or peanuts.

Even as far north as Tientsin, about the

latitude of Cincinnati, we talked with a grower who said he sold from one mow of land (one-sixth of an acre) $40 worth of cabbage, $30 worth of melons and $20 worth of radishes the same season—$540 per acre—but to secure these returns he gave to each of the crops $12 to $18 worth of fertilizer per acre and supplemented the rainfall with irrigation.

The right amount of soil moisture continuously maintained is always and everywhere the first requisite for large yields. In the densely peopled sections of the Far East not only is the rainfall greater than it is in the United States, but a larger proportion of it falls during the summer months when it is most needed and when it can be most effectively utilized. But not only is the rainfall larger in amount and more timely in distribution in China, Korea and Japan, but by planting all crops in rows and hills, practicing intertillage, there is a larger conservation of the moisture which penetrates the soil, and on this account high fertilization

secures relatively larger yields than where intertillage is not practiced.

Notwithstanding the heavy rainfall and good distribution of it in the farthest East, nowhere else in the world are there such extensive systems of irrigation, nowhere is there such conservation of the rain which falls upon the fields and nowhere are there such vast volumes of the run-off from the mountain and hill lands utilized in crop production.

More than 11,000 square miles of land in Japan, and more than half of all their cultivated fields, have been laboriously graded into level terraces, rimmed about to form shallow basins which are held continuously under water from late in June until nearly harvest time. The average area of these rice fields in Japan, speaking of the individual water basin, is but one-fortieth of an acre, about 20 by 50 feet, but measured in the aggregate, as we have said, 11,000 square miles. In China, from the Cantonese delta plains more than 1,000 miles northward to the Yangtse and from Shanghai 1,500 miles

westward such rice fields occur wherever water is available. In Korea we rode past 400 miles of such fields, spread out on the terraced benches on the winding valley plains. No less than 65,000 hills are transplanted on each acre; and when we repeat that 11,000 square miles of land in Japan and several times that area in China are transplanted once and some of the fields twice each year, we have a foundation for reflecting on the mental make-up which has held so many millions of people through the centuries to tasks of repetition like these.

Miles upon miles of canals and distributing ditches have been made by each of these three nations, which must be continuously maintained; likewise must adequate surface and underdrainage be provided and laboriously cared for. In the utilization of water in the growing of rice and other crops, wherever it has been possible to do so by gravity, this has been done, but many thousands of square miles of rice fields are supplied with water by pumping or lifting in

one or another form by human or animal power.

Grading their fields so extensively to a water level and surrounding them with rims, thus compelling the rainfall to leave the fields almost exclusively by transpiration through the crop, by evaporation or by underdrainage, they almost completely eliminate the loss of fertility by wash from their fields. Besides this there is a very extensive practice of constructing reservoirs and of adopting ridge and bed culture in order that as much as possible of the rainfall may be retained, first upon the field itself, where it falls, and second, if there be any excess, in reservoirs, both the furrows of the fields and the reservoirs being compelled to discharge over controlled, raised rims so that practically all silt and most of the soluble plant food may be caught and returned to the fields in the form of canal or reservoir mud. In China the quantities of canal and reservoir mud which are returned to the fields directly or used in making compost are enormous, and we have photographs show-

ing direct applications in single dressings exceeding 70 tons per acre, and yet all of this was carried from the canals in baskets swung from the shoulders of men. Such mud is very rich in organic matter; the liquid form is esteemed equal to human manure in value, though not quite as quick in action, but more enduring. It is often heavily charged with living snails and other animals and shells, and wherever this practice is followed the soils have an abundance of lime.

It is evident that the stress for food among these people led them long ago to adapt themselves to a far less nitrogenous diet than western nations as a rule use and, judging from their well-nourished bodies and their great endurance at hard labor, it seems clear that they have done so with material physical and financial advantage; the rice being rich in carbohydrates derived from the atmosphere rather than from the soil, they draw their energy-producing material from an inexhaustible supply. From a great variety of seeds, too, they extract and use

as food and for export many oils which are hydrocarbons, also derived from the atmosphere. The bean cake, the oilcake, peanut cake and similar products rich in nitrogen and carrying much phosphorus and potash, they have learned religiously to return to their soil, thus economizing and establishing a maintenance efficiency no western nation has approached.

Notwithstanding the fact that in these countries the soils generally are by nature inherently fertile and enduring, persistent, intensive and effective fertilization is everywhere practiced, although not generally through the use of mineral manures other than lime and plant ashes. Centuries ago China and her sister nations learned, or were compelled, to return to the cultivated fields as nearly as possible the entire volume of human waste from every household, whether in city or country, and statistics obtained through the Bureau of Agriculture, Japan, place the amount of human manure in that country, in 1908, at 23,850,295 tons or 1.75 tons per acre of her cultivated land.

The International Concession of the city of Shanghai, in 1908, sold to a Chinese contractor for $31,000, gold, the privilege of entering residences and public places early in the morning of every day in the year and removing the night soil, amounting to 78,000 tons, and taking it to the country for the purpose of selling it to the surrounding farmers, the work being carried on daily during the whole year, for none of the cities in the Far East have hydraulic sewage disposal systems, and throughout these countries human waste is carried to the fields, carefully guarded against loss, and applied with high efficiency to the feeding of crops. In Shanghai, every morning throughout the year the night soil is gathered from each individual household and public place, into covered boats by means of closely covered pails, to go to the fields in the country, where it is stored in receptacles of one or another kind. After it remains in these receptacles for a few days and has lost its injurious effects upon vegetation, it is carried in pails, on the shoulders of men, and carefully dis-

tributed by means of long-handled dippers, where it will be most effective. Foreigners who witness this practice look upon it and upon the burden carriers with disgust, but everywhere the world over every good mother, in the care of her infant, submits cheerfully to all that is unpleasant, if unavoidable. In the same spirit these people accept what has seemed to them the best solution under their conditions, making the most possible from the wastes, and we admire them, as we do the mother, for their ability to do so.

Where canals are not available such wastes are transported in closed receptacles on the shoulders of men, on the backs of animals, on wheelbarrows, and on carts. In riding by ricksha into the country out of Kyoto, Japan, early one morning we passed, during a three-fourths hour ride, along a single highway, 52 cartloads of human manure, drawn either by men or cattle, each cartload carrying five to 12 receptacles holding not less than 60 pounds each; and on our return, after two and a half hours, the

procession was still moving in the same direction and we passed 61 similar loads. This is an indication of the magnitude of the movement into the country along a single highway leading out of one of Japan's large cities.

We found the prices paid by farmers in Japan and China for fresh human manure to range between $1 and $2, gold, per ton, and in the Shantung province, where it is used dry, $18 per ton. From these data it may be correctly stated that Japan, through her utilization of her night soil, avoids the importation of from $23,800,000 to $47,600,000 worth of commercial fertilizers, while the people of western nations are expending larger sums of money as the cost of throwing away like amounts of fertilizers.

The perennial source of soil nitrogen these people had discovered in very early days, and their consistent, persistent and efficient cultivation of legumes is remarkable in view of the fact that it is centuries old. Nearly one-fifth of the dry land fields in

Japan are annually occupied by some nitrogen-gathering crop, adding nitrogen to the soil of the dry land fields. Then, on the rice fields and as a winter crop alternating with the rice, legumes are extensively grown, especially where green stuff from the hill lands is not readily available, and for the express purpose of producing green manure. Just before or immediately after the rice crop is harvested fields are often sowed to "clover" (*Astragalus sinicus* or *lotoides*), which is allowed to grow until near the next transplanting time, when it is either turned under directly, or more often (in the canalled regions in China) stacked along the canals and saturated while doing so with soft mud dipped from the bottom of the canal. After fermenting 20 or 30 days it is applied to the field. One acre of this vetch is commonly applied to three or four acres of rice, giving 1.5 to 5 tons of the green produce and as much more soft canal mud per acre.

With one acre of land in the green manure crop, grown between the rice harvest

Fig. 28—Rice fields with grass distributed over them, to be worked in as a fertilizer. The man at work is covering the grass beneath the mud. Japan.

Fig. 29—Field being flooded preparatory to plowing for rice. It is manured with clover which has been composted with canal mud about 20 days and has the general appearance of very rotten silage, but a much stronger odor. The cow which is working the pump can be seen under the pump shelter in the background and another cow, by the telegraph pole, is ready to draw the plow. Kiangsu Province, China.

Fig. 30—Village in Shantung Province, China. Donkey grinding grain. Small compost stack in foreground, at right.

Fig. 31—Fitting ground for a crop of sweet potatoes. A fertilizer of dry, pulverized composted earth, manure and ashes mixed, about half earth, had been applied at the rate of 7,400 pounds per acre. The plow was drawn by a cow and donkey. Shantung Province, China.

of one season and the time of transplanting the next, there are left two or three acres to bear other crops. One of these may be rape, another may be wheat or barley, so that each year, in the rice country, there follows the rice crop either some humus-nitrogen producing crop, or rape, wheat or barley. There is thus maintained a systematic rotation, notwithstanding the fact that the fields may be in rice every year.

Where a family is too large in proportion to the amount of their land, so that they cannot afford to spare any of it on which to grow the humus and the nitrogen-producing "clover," men may be seen in the canals working in water up to their armpits with an appropriate tool, cutting grass for compost. Or if this is not available the mother and children may go together, with their baskets, up the hill or mountain sides for green herbage growing there, and in these cases, too, knowledge and good judgment are displayed in selecting the vegetation which makes the best fertilizer, unless there is a shortage so that everything must be cut.

In China, in Korea and in Japan all but the most inaccessible of their extensive mountain and hill lands have long been taxed to their full capacity for fuel, lumber and herbage for use as green manure or in making compost; and the ashes of all of the fuel and of all the lumber used at home ultimately finds its way to the field.

In the Kiangsu province, and in Chekiang, Kwangtung and others in China, where canals are numerous, animal manure and solid organic wastes are piled along the canal banks, building the material into heaps mixed with thin mud dipped from the canal bottom, thus returning to the fields both the silts washed from them and the organic matter which has become associated with it, the combination making a better fertilizer than either alone.

In the provinces where most of the travel is by land along roads, men, women and children may often be seen early and late with a pair of baskets swung from the carrying pole over their shoulders, and the gleaning fork, gathering up the droppings of

manure along the roads. These are taken to the homes to add to their fertilizer supplies or, if the gleaners are without land, it is sold to those who have and thus becomes a way for them to supplement their earnings when more remunerative service is not their fortune. Even the droppings of silkworms are carefully collected and carried back to the mulberry orchards, where the surface soil, to a depth of three or four inches, is removed in a circle about the trunk of each tree and a dressing of this manure applied as a fertilizer, the soil being returned to cover it.

In the drier provinces the coarse organic matter decays too slowly if applied directly to the soil, and interferes with the capillary movement of soil moisture, and hence something like two to four tons of soil or subsoil per acre of cultivated field are laboriously carried into the farm villages for use in the preparation of plant food. Each household has its compost pit whose size is proportioned to the land to be served. In this all the animal manure and the waste and rough-

age from the fields are fermented under water during three to six months. Wheat and millet are even pulled by the roots and the roots either burned for fuel and the ashes saved or they are fermented in the compost pits. When such material has been thoroughly rotted it is removed from the pit, spread out upon the streets or threshing floor, mixed with soil, repeatedly stirred and turned, thus carrying it through the old process of niter farming until, by the fermentation of the organic matter, nitrates have been formed from the potash, magnesia and lime carbonates in the fuel ashes and in the soil, finally producing a fertilizer rich in humus and highly charged with all of the essential plant food elements in available form, compounded from every possible waste of the field, the ashes of the fuel, the liquid and solid wastes of the home and stable, and soil and subsoil from the field, here again prolonging their allotment of time and compensating for their limited fields by forcing portions of soil and its microscopic life to work between crops and

off the field in elaborating immediately available plant food, which is used, as they say, in "feeding the plants" in contradistinction to manuring the soil.

In the colder provinces of Shantung, Chihli and north into Manchuria, in order to utilize the waste heat from cooking, a long, broad, horizontal flue, upon which beds may be spread, extends from the kitchen through two or more sleeping apartments before it is carried out through the roof. These flues are built out of sun-dried brick made from soil or subsoil mixed with short straw or chaff. The brick are often one foot square and four inches thick, so that a large volume of earth is required for the construction. After two to four years' use these flues, through the decay of the organic matter and shrinkage, become more or less open and the draft defective, so that they must be replaced. But these people have learned that the soil of such brick, after use in the range and flues, is the best possible earth for composting, and so the saving of fuel in securing warmth for the bed at night

and for the apartments by day is at the same time made to do duty in the production of fertilizer for the field, and this may serve as an illustration of one of a thousand ways in which the greatest economy is practiced along so many lines except in the matter of human labor.

A large proportion of this earth compost is rendered air dry and finely pulverized, so that it may be economically and evenly distributed in the field. Sometimes it will be planted in the hills or in the drills with the seed; sometimes it will be sowed in a drill alongside the row and covered in. When we saw it used for sweet potatoes, just ready for transplanting, a shallow furrow was struck through the field with the plow drawn by the donkey-and-cow team. The prepared fertilizer had been drawn to the field and was distributed in piles. Behind the plow a man followed with the fertilizer in a basket, distributing it along the furrow, which was then turned back over the fertilizer, two other furrows turned, forming a ridge, its summit leveled and smoothed

with a hand harrow, and the sweet potatoes transplanted directly above the fertilizer.

The Japanese experiment stations issue instructions as to the best methods of making and caring for compost. In some of the prefectures subsidies are provided from which farmers are paid at the rate of 5 yen, or $2.50, for the preparation of a compost heap on their own places, covering 20 to 40 yards and having the standard height. In other prefectures premiums are offered for the best compost heaps, and committees are appointed to judge and award the premiums.

If there is time and favorable moisture conditions for nitrification to occur in the field, the prepared compost may be carried, wet or partially dried, and applied directly to the soil, doing what they call "manuring the land" in contrast with "feeding the plants." It was this practice of highly charging soil rich in lime with organic matter, frequently wetting it with old urine and liquid manure, turning and stirring it to keep it well aerated, that, in olden times,

constituted what was known as niter farming in Europe. Its object was the production of saltpeter or potassium nitrate for the manufacture of gunpowder. But saltpeter is one of the best of plant foods, for it carries both nitrogen and potash in the form most readily assimilated by plants. If lime carbonate is present in the soil rich in organic matter, instead of potassium carbonate, lime nitrate will be formed and this, too, is an available source of nitrogen for plants. This is one of the reasons why soils should be well supplied with lime and why soils rich in lime are so generally fertile.

It cannot be emphasized too strongly or repeated too often that the frequent cultivation of a soil rich in humus, rich in lime, potash or magnesium carbonate, and rich in moisture, is in fact niter farming on a field-wide scale whereby nitrates, which are plant food nitrogen, are produced in the soil. Fitting the rich soil to be planted to corn or potatoes, two or three weeks before the time for planting and then disking or harrowing to save moisture and kill one or two

crops of weeds before planting, has the other advantage of enriching the soil in immediately available plant food. The old Chinese farmers here referred to, in order to save time, to save room, and in order to be able to bring the plant food to the crop at the time when it can utilize it best, carry the soil to the villages, enrich it to the highest limit it will stand and work with it until very highly charged with available plant food, literally growing their humus and much of the available plant food which may be derived from it in their villages and at their homes where they can better use available spare moments, and then transport it to the fields at opportune times. To me this whole story would be a wonderful one if it could be worked out in its details and illuminated by the science which underlies its practice.

It is very evident, too, that they have long ago become convinced that no system of rotation of crops and of tillage combined can alone maintain a sufficiently high maintenance capacity of soil to meet the demands

of such dense populations as theirs, for the amount of time and labor which they devote to fertilizing is enormous. Our farmers need to remember, too, in this connection, that these extensive, persistent and rational practices in fertilization are applied to soils naturally quite as fertile and enduring as the best of ours, and they are persisted in in a warmer climate, with more rainfall, having a better distribution than we have in most parts of the United States, and each of these conditions materially augments the efficiency of plant food carried by the soil and developed in it. In the face of all this there is not the slightest ground to hope that the best possible systems of rotation of crops, coupled with the maintenance of the best possible physical conditions of the soil, can together be made to produce the amount of food which such dense populations as exist in the Far East require. Adequate and rational fertilization must in some way be combined with the other two. Let us hope that the farmers of the future may be helped to lighten the enormous burden which is

now being carried by the farmers in the Far East and which they have carried through all the centuries. Such results as they are getting we must get. Can we secure them with less of bodily effort and with more time for worthy enjoyment and intellectual life?

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